Abstract

Parabolic resection, named for the shape of the cut edges of the excised tissue, expands on a common ‘trick’ used by experienced mitral surgeons to preserve tissue and increase the probability of successful repair. Our objective was to describe and clinically analyze this simple modification of conventional resection. Thirty-six patients with mitral regurgitation underwent valve repair using parabolic resection in combination with other techniques. Institution specific mitral data, Society of Thoracic Surgeons data and preoperative, post-cardiopulmonary bypass (PCPB) and postoperative echocardiography data were collected and analyzed. Preoperative echocardiography demonstrated mitral regurgitation ranging from moderate to severe. PCPB transesophageal echocardiography demonstrated no regurgitation or mild regurgitation in all patients. Thirty-day surgical mortality was 2.8%. Serial echocardiograms demonstrated excellent repair stability. One patient (2.9%) with rheumatic disease progressed to moderate regurgitation 33 months following surgery. Echocardiography on all others demonstrated no or mild regurgitation at a mean follow-up of 22.8±12.8 months. No patient required mitral reintervention. Longitudinal analysis demonstrated 80% freedom from cardiac death, reintervention and greater than moderate regurgitation at four years following repair. Parabolic resection is a simple technique that can be very useful during complex mitral reconstruction. Early and intermediate echocardiographic studies demonstrate excellent results.

Keywords: Echocardiography; Heart valve; Mitral systolic anterior motion; Mitral valve; Mitral valve repair

1. Introduction

Mitrail valve repair is clearly superior to replacement for the treatment of non-myopathic regurgitation [1]. However, overall mitral repair rates in Europe and the USA remain at ~46% [2, 3]. Even under the ideal circumstances of elective first operations for isolated mitral regurgitation without stenosis or endocarditis, ~30% of valves were not repaired in 2007 [4]. With over 16,000 mitral operations performed annually in the USA alone [3], continuing efforts to increase the probability of repair are important.

Carpentier’s landmark work emphasized mitral repair techniques involving leaflet resection [5, 6]. Recent laboratory and clinical evidence supports preservation of leaflet tissue and coaptive surface enhancement [7–9]. Expanding on a common ‘trick’ used by experienced mitral surgeons, a specific tissue preserving technique was mathematically modeled and clinically introduced. Parabolic resection, named for the shape of the cut edges of the excised tissue, provides a simple modification of triangular, quadrangular and segmental resections that can be particularly useful during difficult repairs. This study presents the first clinical series using parabolic resection to correct mitral regurgitation.

2. Materials and methods

2.1. Mathematical model and concepts

This mathematical model will introduce the concept of parabolic resection. The model is descriptive and is not intended to be a definitive mathematical proof.

Following leaflet tissue removal in the typical quadrangular or segmental resection, the annulus is plicated or compressed thus bringing the bases of the leaflet edges together. If the lines of resection are parallel then approximating the cut edges will largely replicate the original sagittal contour of the leaflet with a modest uniform reduction in height of coaptation due to the radial displacement of the chords. The transition of leaflet tissue from the horizontal plane of the annulus to the vertical plane of coaptation as seen in the sagital view can be described mathematically as the 90° arc of a circle or an ellipse. This is demonstrated by the gray curve in Fig. 1. Mathematically the x and y relationship of a standard triangular, quadrangular or segmental resection viewed sagitally is approximately described by \( c = x^2 + y^2 \) or \( y = (c-x^2)^{1/2} \) where \( c \) is a constant.
The circumstances of the posterior leaflet parabolic resection are substantially different. If we assume that the parabolic curves excised are described by inversion of the simple parabola $y = x^2$ for each cut edge then, in the sagittal view, the downward displacement of the leaflet tissue as it is approximated from the annulus to the free edge will be accelerated by the increasing width of resection. This acceleration is the result of closure of the two opposing parabolae whose rapidly increasing separation $2x^2$ exponentially increases the radial displacement of the chords below the cut edge of the leaflet. As these edges are approximated, the free margin is drawn much more rapidly toward the ventricular apex. The transition of the leaflet tissue from the horizontal plane of the annulus to the vertical plane of coaptation in the sagittal view is now more accurately described by a higher level function rather than the simple circle or ellipse. The $x$ and $y$ relationship of a parabolic resection viewed sagitally may be approximately described by $y = (c_1 - c_2x^2)^{1/2}$ where both $c_1$ and $c_2$ are constants. The transition from the plane of the annulus to the plane of coaptation occurs more rapidly and closer to the free margin of the leaflet. This is illustrated by the black curve in Fig. 1.

The circumstances of anterior leaflet triangular resection are more complex due to the semicircular shape of the leaflet. A conventional triangular resection with linear edges of excision results in progressive uniform radial displacement of the chords as the cut edges of the excision are approximated. Therefore, the transition from the plane of the annulus to the plane of coaptation extends from the apex of the excised triangle to the free margin. This suture line tends to bend abruptly at the apex of the triangle and often produces a poorly defined vertical plane of coaptation.

When the parabolic technique is used, considerably less tissue is removed. This is particularly true near the apex of the triangle. Therefore, the initial transition from the apex of the resection to the midpoint of the resection is more gradual and thus decreases the tendency toward abrupt bending at the apex. Again, the transition from the plane of the annulus to the plane of coaptation occurs more rapidly and closer to the free margin of the leaflet. The echocardiographic results of both anterior and posterior parabolic resections are demonstrated in Fig. 2.

2.2. Indications and description of technique

In this series parabolic resection was indicated for mitral valve reconstruction in three circumstances. Note that the circumstances vary considerably. The parabolic resection was useful with fibroelastic deficiency when little tissue is available. The rapid transition from the plane of the annulus to the plane of coaptation simultaneously maximizes leaflet surface area and coaptive surface length (Figs. 3 and 4). At the other extreme the parabolic was useful with Barlow’s disease when excessive tissue was present. Following posterior leaflet resection, the rapid transition from the plane of the annulus to the plane of coaptation prevented systolic anterior motion by eliminating displacement of the anterior leaflet into the left ventricular outflow tract (Fig. 5). The parabolic technique was particularly useful for the prevention of systolic anterior motion and for adjusting leaflet height following sliding posteroplasty (Fig. 4). Finally, anterior leaflet prolapse was corrected with minimal leaflet distortion by using a parabolic modi-
Fig. 3. Limited posterior segment prolapse with minimal available tissue. (a) The three segments of the posterior leaflet are demonstrated as viewed from the left atrium. The central marginal chords of P2 have ruptured. (b) Ruptured or elongated marginal chords are removed. (c) The dashed lines represent the boundaries of a standard quadrangular resection of central P2. The parabolic resection is represented by the dotted lines. A narrower resection of the central portion of the segment is performed with care being taken to preserve ample tissue adjacent to the intact marginal chords of P2. The edges of the resection are then trimmed to approximate the shape of mirror image inverted parabola. Secondary chords adjacent to the resection are divided. (d, e) Simple annular plication is typically performed. (f) The cut edges of P2 are approximated.

Fig. 4. Coaptation alignment adjustment. (a) This coronal (commissural) view demonstrates P2 prolapse. The parabolic resection is performed as described in Fig. 3c–f. (b) As the cut edges are approximated, the chords assume a more oblique attachment to P2 pulling the leaflet toward the ventricular apex. The sagittal views of A2 and P2 are shown in the inset illustrations. Inset b demonstrates overcorrection of P2. The free margin extends too far toward the ventricular apex thus creating iatrogenic restriction of P2 and a potential leak. (c) The posterior leaflet height is adjusted simply by removing one or two stitches at the margin of the repair. This adjustment relieves the restriction and allows precise alignment of the anterior and posterior leaflet coaptive surfaces. Conversely, residual prolapse can be corrected by placing additional sutures at the free margin of the repair.

Averages for continuous variables, such as age and ejection fraction are reported as the mean ± standard deviation (S.D.). The Carpentier systems for segmental nomenclature and functional classification were used for identification and analysis of dysfunction.

Cardiac valve intervention reporting guidelines jointly published by the American Association for Thoracic Surgery, European Association for Cardio-Thoracic Surgery and Society of Thoracic Surgeons were used and provide the following definitions. Surgical mortality is reported as all-cause mortality within 30 days. Cardiac death is defined as all deaths resulting from valve deterioration, non-structural dysfunction, valve thrombosis, embolism, bleeding events, or operated valve endocarditis and includes unexplained death. Reintervention is any surgical or percutaneous pro-

2.3. Methodology and definitions

Institution specific mitral data, Society of Thoracic Surgeons protocol data and preoperative, post-cardiopulmonary bypass (PCPB) and postoperative echocardiography data were obtained and analyzed on all patients. No patients were lost in follow-up. In accordance with published recommendations, the demographics, echocardiographic findings, intraoperative analysis, surgical procedures and outcomes were documented prospectively at the time of acquisition with subsequent database entry and retrospective review. Echocardiographic data were obtained using American Society of Echocardiography guidelines. Mitral regurgitation was graded in accordance with American College of Cardiology/American Heart Association and European Society of Cardiology guidelines as mild (1+), moderate (2+) or severe (3–4+).
Parabolic resection was most often useful when correcting complex dysfunction, such as bileaflet prolapse. Nineteen patients (53%) had Barlow’s disease or forme fruste with sufficiently redundant leaflet tissue such that posterior segmentectomy was indicated. Isolated posterior leaflet repair using a limited parabolic resection was performed in 12 patients (33%). Eight patients (22%) required anterior leaflet parabolic resection.

Note that this was a complex subgroup of patients for which multiple techniques were often required. Additional mitral procedures included papillary muscle shortening (14), sliding posteroplastic (13), annular plication (13), en bloc annular calcium resection (2), anterior leaflet augmentation (1), anterior leaflet peel (1), papillary head reattachment (1), chordal transfer (1), artificial chord placement (1), and septal myectomy (1). Following tissue reconstruction, all 36 patients received a Carpentier–Edwards Physio remodeling annuloplasty ring (Edwards Lifesciences, Irvine, CA, USA).

Additional cardiac procedures included coronary artery bypass grafting (8), atrial ablation (5), atrial septal defect/patent foramen ovale closure (5), aortic valve replacement on a previously repaired valve. Patient follow-up was active using both anniversary and cross-sectional modes. Approval for retrospective analysis was received from the Munson Medical Center Institutional Review Board 17 March 2006.

### 2.4. Patient population

Between January 2004 and June 2009, 36 consecutive patients underwent mitral valve repair using parabolic resection. Follow-up was complete on all patients. Ages ranged from 40 to 86 years with a mean age of 62 ± 13 years. Seventy-two percent were men, 44% were hypertensive and 8% were diabetic. As determined by preoperative transthoracic echocardiography, all had moderate to severe mitral regurgitation with a mean left ventricular ejection fraction of 60% ± 6%. The disease etiology was myxomatous degeneration in 24 patients (67%), fibroelastic deficiency in eight (22%), rheumatic or dystrophic calcification in three (8%) and ischemic papillary rupture in one (3%).

### 2.5. Surgical procedures

Fig. 5. Complete posterior segment prolapse with excessive tissue. This left atrial view demonstrates a nearly completed mitral repair for Barlow’s disease. (a) The papillary muscles have been shortened (or neochordoplasty performed), P2 has been completely excised, the appropriate wedge resections have been performed at the bases of P1 and P3, compression sutures have been placed, and P1 and P3 have been reattached to the annulus using the sliding technique. Despite adequate wedge resections, the marginal edges of P1 and P3 still extend too far toward the anterior annulus and may distort A2 and/or result in systolic anterior motion. This can be corrected using a parabolic resection. (b) The edges of P1 and P3 adjacent to the P2 resection are trimmed to approximate the shape of mirror image inverted parabolae. (c, d) The reshaped edges of P1 and P3 are approximated thereby rolling the margin of the posterior leaflet toward the ventricular apex. (e) The repair is completed with an appropriate annuloplasty ring. The posterior coaptive surface can now be precisely aligned using marginal suture adjustment as described in Fig. 4.

Fig. 6. Anterior segment prolapse. (a) The large anterior leaflet of Barlow’s disease is demonstrated. Central A2 prolapses above the plane of the annulus (inset A). (b) A narrow triangular resection of the central portion of A2 is performed and the cut edges are shaped like mirror image parabolae. (c) The cut edges are approximated.
(1), and tricuspid valve repair (1). Two patients had previously undergone non-mitral cardiac operations.

3. Results

One patient (2.8%) died within 30 days of surgery from sepsis of unknown etiology. A second death occurred approximately three months following surgery from witnessed aspiration due to well documented severe esophageal and epiglottic dysfunction. No patient required valve replacement after attempted repair or mitral reintervention of any type.

The echocardiographic findings preoperatively and following parabolic resection are summarized in Table 1 and Fig. 7. All repairs remained stable except for one patient with rheumatic disease who progressed to moderate regurgitation 33 months following surgery. Mean echocardiographic follow-up was 22.8 ± 12.8 months. Life table analysis demonstrates 80% freedom from cardiac death, reintervention and greater than moderate regurgitation up to four years following repair (Fig. 7).

4. Discussion

The standard techniques for the correction of mitral regurgitation occasionally produce unacceptable results. Potential etiologies for repair failure include a suboptimal coaptive surface due to insufficient residual leaflet tissue, abrupt bending or folding of the tissue following reapproximation and systolic anterior motion. With more complex repairs, it may be difficult to anticipate the effect of resection or artificial chords on alignment of the coaptive surfaces. In our experience, parabolic resection was of great utility when standard resection techniques would result in the removal of too much leaflet tissue. The parabolic technique creates a smooth, more ideally contoured surface at the transition from the plane of the annulus to the perpendicular coaptive surface. Parabolic resection allows for adjustment of the height of coaptation which facilitates precise alignment of the coaptive surfaces and the elimination of residual prolapse or iatrogenic restriction. Finally, in the presence of excessive tissue, the parabolic technique was useful for the prevention of systolic anterior motion.

This study has several limitations. The retrospective nature of this analysis is associated with well known statistical limitations, however, we considered blinded, prospective randomization to be ethically inappropriate [15]. Most of the patients required complex repairs and therefore parabolic resection was often accompanied by numerous other techniques. As a result this analysis is not restricted to the evaluation of the parabolic technique alone. Finally, though a mathematical model using two mirror image parabola is reasonable, in actual practice cutting a parabola from leaflet tissue is far from exact. It is obvious that the parabolic model can only be roughly approximated in the operating room and that this technique still requires expert surgical judgement. Nonetheless, an understanding of the parabolic concept can be extremely useful during difficult repairs.

Parabolic resection is a simple, tissue sparing modification of conventional resection that can be easily adjusted and used to prevent systolic anterior motion. Early and intermediate echocardiographic data demonstrate excellent results. Though familiarity with this concept can be important during challenging cases, it is not intended to routinely replace other well established techniques. Surgeons proficient in mitral reconstruction may find parabolic resection useful for increasing the initial success and subsequent durability of mitral valve repair.

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References


eComment: Physiological chordal stress sharing

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This type of repair also enhances strut, secondary and marginal chords re-alignment on the coaptation plane, thus favouring the re-establishment of the physiological systolic stress sharing (2) [see video and paper at: http://www.fondazionecarrel.org/carrel/cardiac/files/physio/physiofulltext.htm], which protects marginal chords from further rupture.

References
