

The Role of Chordae Tendineae in Mitral Valve Competence

Daniel M. Espino¹, Duncan E. T. Shepherd², David W. L. Hukins², Keith G. Buchan³

¹Department of Biomedical Physics and Bio-Engineering, University of Aberdeen, Foresterhill, Aberdeen, ²School of Engineering, Mechanical Engineering, The University of Birmingham, Birmingham, ³Cardiothoracic Surgery, Aberdeen Royal Infirmary, Aberdeen, UK

Background and aim of the study: The study aim was to understand the role of different mitral valve chordae tendineae, and how damage to them affects valve competence.

Methods: A test apparatus was used to apply pressure to porcine mitral heart valves that were intact and have had selected chords severed. Anterior leaflet strut and marginal chords were selectively severed, as were posterior leaflet basal and marginal chords. Commissural chords were also severed.

Results: Severing anterior leaflet marginal chords ($p = 0.018$) and commissural chords ($p = 0.018$) significantly reduced mitral valve competence. Severing posterior leaflet marginal and basal chords, and ante-

rior leaflet strut chords, had no significant effect in reducing the pressures that the valves could withstand. Severing a mixture of posterior leaflet basal and marginal chords significantly reduced the pressure withstood by the valves ($p = 0.004$).

Conclusion: The study results confirmed that anterior leaflet marginal chords, but not strut chords, are vital for valve competence. Commissural chords were also shown to be vital for mitral valve competence. Several posterior leaflet chords had to be severed to affect mitral valve competence.

The Journal of Heart Valve Disease 2005;14:603-609

An experimental method and apparatus described previously (1) has been used to investigate the role of the anterior leaflet, posterior leaflet and commissural chords in mitral valve competence. The method involves the application of water pressure to the mitral valve from the side corresponding to the left ventricle. The pressure is increased until the valve fails, as demonstrated by water flowing through the valve. In the present study, the role of chords in mitral valve competence was investigated.

Although mitral valve failure is life-threatening, it can be corrected by surgery (2-4). The mitral valve is composed of an anterior and posterior leaflet, connected to papillary muscles (that are attached to the left ventricle) by chords (Fig. 1). A distinction is often made between marginal chords that insert into the edge of the leaflets, and basal chords that insert away from the free edge of the leaflet between the free edge and the mitral valve annulus. Marginal chords are thinner than basal chords, and have been found to be

stiffer (5,6). Two thick basal chords that insert into the anterior leaflet are known as strut chords, while the chords that insert in the areas in between the anterior and posterior leaflet are known as commissural chords. Further detail on the nomenclature for the chords can be found elsewhere (7).

Several studies have investigated the role of strut chords (8-13) and their associated marginal chords (9,12). Anterior leaflet marginal chords, but not strut chords, have been found to be vital for valve competence (9,12). One study reported that severing strut chords reduced aortic flow in an isolated working pig heart model (12), while another showed that strut chords allow the mitral valve anterior leaflet to form an inflow and outflow funnel from the left ventricle during diastole and systole, respectively (8). The methods used include in-vivo testing in animals such as sheep (8,10,11,13) and the use of an isolated pig heart model (12), where a heart is used whilst still pumping. The one study that investigated the role of anterior leaflet chords in vitro also attempted to replicate the normal pumping action of the heart (9). In-vitro experiments enable experimental conditions to be carefully controlled. Although the method used for the present study does not mimic the pumping action of the heart, it does enable the regurgitation pressure to be used as

Address for correspondence:

Dr. D. E. T. Shepherd, School of Engineering, Mechanical Engineering, University of Birmingham, Edgbaston, Birmingham, B15 2TT, UK

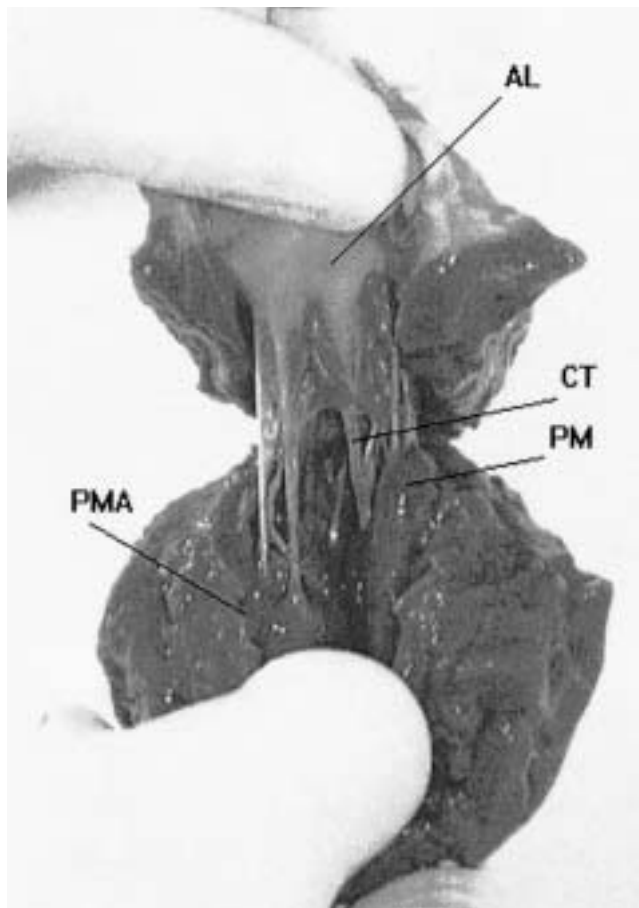


Figure 1: Anterior view of a specimen dissected for testing mitral valve failure. AL: Anterior leaflet; CT: Chordae tendineae; PM: Papillary muscle; PMA: Papillary muscle annulus.

a direct measure of the effect of severing chords.

To date, there appears to be no in-vivo or in-vitro published studies investigating the role of the posterior leaflet chords or commissural chords on mitral valve competence. Therefore, mitral valves have been tested in vitro, where anterior leaflet strut and marginal chords, posterior leaflet marginal and basal chords, and commissural chords have been severed to investigate their role on valve competence.

Materials and methods

Tissue specimens

All experiments were performed using porcine hearts that are an established geometrical model for human hearts (14). Commercially available hearts (Fresh Tissue Supplies Ltd., Horsham, West Sussex, UK) were wrapped in tissue paper soaked with physiological saline, placed in heat-sealed plastic bags, and stored at -40°C .

Specimens were dissected from thawed hearts. These

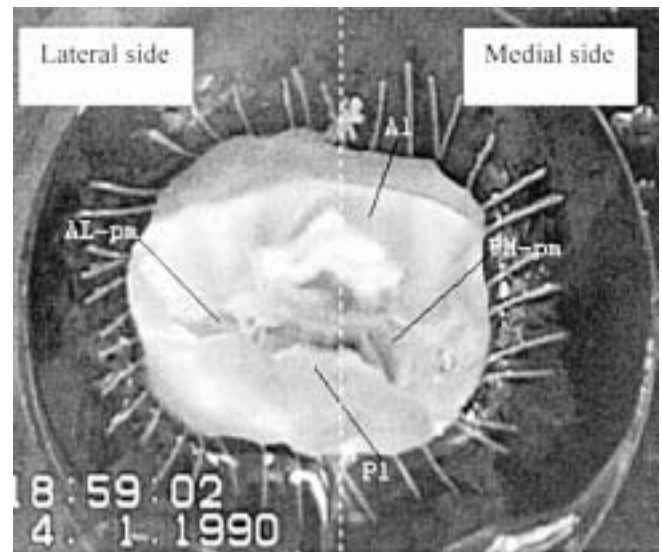


Figure 2: Mitral valve viewed from the side corresponding to the left atrium. The anterior and posterior leaflets are visible. The dotted white line runs through the middle of the anterior and posterior leaflets, separating the lateral and medial side of the valve (labeled) into which lateral and medial chords insert, respectively. Anterolateral commissural chords are attached to the anterolateral papillary muscle, and posteromedial chords to the posteromedial papillary muscle. AL: Anterior leaflet; AL-pm: Anterolateral papillary muscle; Pl: Posterior leaflet; PM-pm: Posteromedial papillary muscle.

consisted of a ring of muscle around an intact mitral annulus. The papillary muscles were left attached to a ring of left ventricular muscle (the 'papillary muscle annulus'). The base of the left ventricle was removed to allow fluid to flow towards the valve leaflets. A strip of muscle between the mitral annulus and papillary muscle annulus was also removed, to expose the chords that lie underneath. Select chords could then be severed during testing. A dissected specimen is shown in Figure 1.

Experimental procedure

Experiments performed involved the sequential severing of selected chords. This was followed by determination of the pressure required to cause mitral valve regurgitation (i.e. valve failure). Details of the apparatus used for measuring the failure pressure and the method of mounting the specimens described in the previous section, have been published previously (1). Six specimens were tested in each of the five sets of experiments performed; thus, a total of 30 specimens was tested. Each specimen was initially tested intact, ten times, to determine the normal function of the valve. Likewise, after selected chordal severing the valve was tested ten times, to determine the function of the damaged valve.

In each test the water pressure contained by the valve was increased at a rate of approximately 33 mmHg/s (or 4.4 kPa/s; 1 mmHg = 133 Pa). The test was stopped either when fluid flowed through the valve or after the pressure in the test chamber exceeded 150 mmHg (20 kPa). An intact valve (i.e. before any chords were severed) was deemed to be fully competent if no regurgitation occurred when the pressure applied to the closed valve increased to 150 mmHg (20

kPa). A pressure of 150 mmHg was chosen, to prevent lasting damage to the specimen being tested (i.e. so that chordal cutting could be performed and the specimen re-tested) while still pressurizing the mitral valve specimen to above a textbook physiological range (15).

The conditions for each of the five sets of experiments are detailed in Table I. In each set, the chords were severed in the order described. In tests involving the posterior leaflet, only the chords that attach into the middle of the three leaflets (or scallops) were severed. The chords that insert into the anterior leaflet and posterior leaflet (middle scallop) do not insert into the middle of the leaflet; rather, they insert laterally into the leaflets or scallops (i.e. either side of the middle). They do this so as to form arcading connections with adjacent chords through the substance of the valve leaflet.

Chords that insert lateral to the center of the valve leaflet (Fig. 2) were referred to as lateral chords. Similarly, chords inserting medial to the center of the valve leaflet were referred to as medial chords. Commissural chords were named as anterolateral and posteromedial, depending on the papillary muscle to which they were connected (see Fig. 2).

Statistical analysis

The mean \pm SD and median were calculated for each data set. The data were found not to be normally distributed, as assessed by the Anderson-Darling normality test. The Wilcoxon Signed Rank Test, which is a non-parametric test for paired data, was therefore used to compare the pressure withstood by the intact valve and the pressure withstood by the valve after chordal cutting.

Results

Anterior leaflet

Severance of the anterior leaflet marginal chords resulted in incompetent mitral valves (Table II). The tested mitral valves failed at 0 mmHg (c.f. 143 ± 11 mmHg for intact valves) - that is, they provided no resistance to the flow of water through the valve. After the lateral marginal chords had been severed, four of the six valves tested could not be pressurized up to or above 30 mmHg. The pressure withstood by the valve with cut marginal chords was significantly less than that withstood by the intact valve. Figure 3 shows the anterior leaflet prolapse that occurred after marginal chords were severed. Marginal chords prevent the anterior leaflet from freely prolapsing, and keep the anterior leaflet in place against the posterior leaflet when pressure is applied against the closed valve. It is clear from Figure 3b that fluid flowed freely out of the valve after marginal chords had been severed.

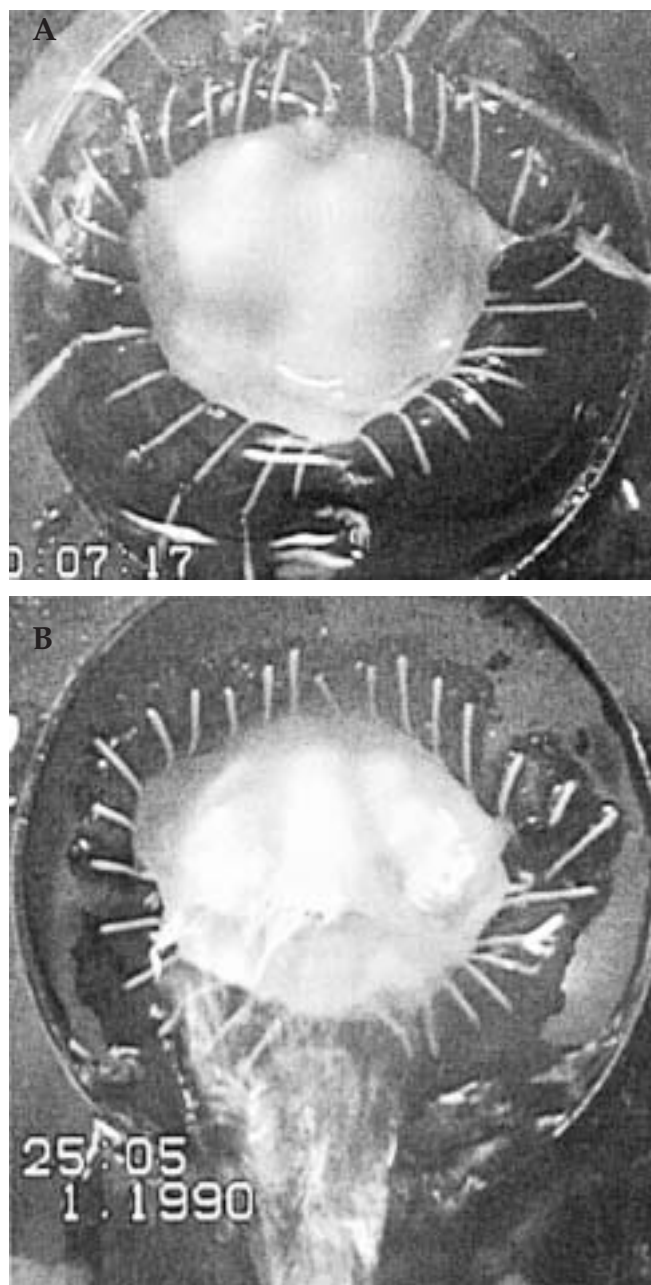


Figure 3: Mitral valve during testing. a) When the valve is intact. b) After marginal chords attached to the anterior leaflet have been severed; in this case the anterior leaflet is free to prolapse. The image was taken from the side corresponding to the left atrium.

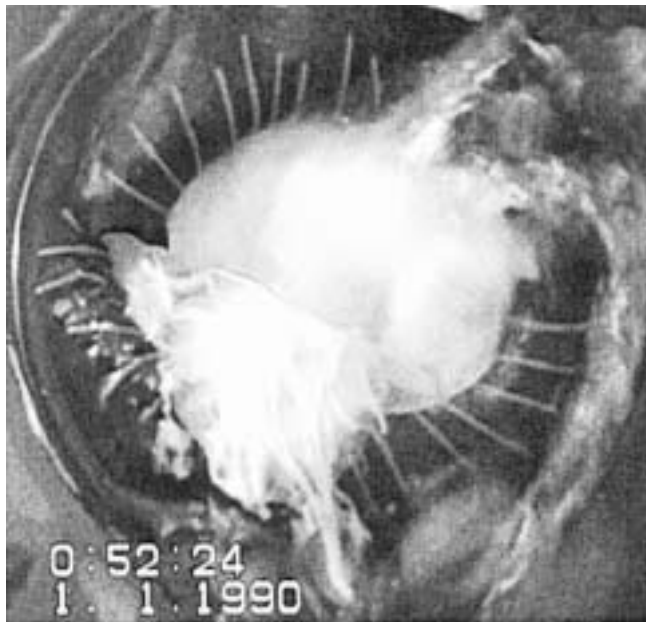


Figure 4: Mitral valve during testing after all basal and marginal chords attached to the middle scallop of the posterior leaflet have been severed. Complete prolapse of this segment of the posterior leaflet is observed. The image was taken from the side corresponding to the left atrium.

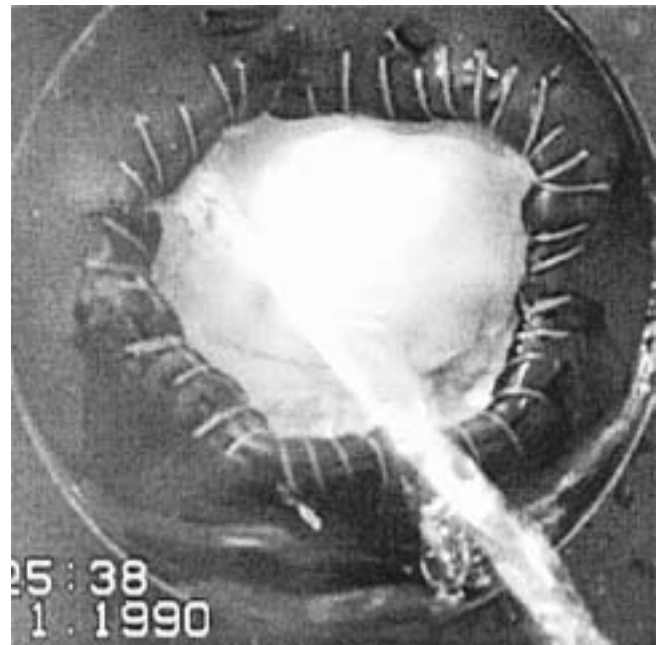


Figure 5: Mitral valve during testing after anterolateral commissural chords have been severed. Fluid can be seen to regurgitate; a small prolapse of leaflet tissue where the commissural chords were severed can be observed. The image was taken from the side corresponding to the left atrium.

There was no significant difference between the pressure that the intact valve withstood (148 ± 4 mmHg) and the pressure withstood after severing the anterior leaflet strut chords (142 ± 12 mmHg) (Table II).

Posterior leaflet

Severance of the posterior leaflet basal chords had no significant effect on mitral valve competence (see Table II). After severing all posterior leaflet basal chords, the valves withstood pressures of 123 ± 61 mmHg (c.f. 147

± 8 mmHg for intact valves). The reduction in average pressure withstood by the valves was caused by the complete failure of one of the six valves tested.

Severing posterior leaflet marginal chords had no significant effect on mitral valve competence (see Table II). After severing all the posterior leaflet marginal chords, the valves withstood pressures of 141 ± 21 mmHg (c.f. 150 ± 0 mmHg for intact valves).

The data in Table II show that severing a mixture of marginal and basal chords reduced valve competence.

Table I: Details of the five sets of experiments in which chords were severed.

Experimental set	Order of chordal cutting			
	First	Second	Third	Fourth
1	AL-S1	AL-S2	N/A	N/A
2	AL-M1	AL-M2	N/A	N/A
3	PL-B1	PL-B2	PL-B2&M1	PL-B2&M2
4	PL-M1	PL-M2	PL-M2&B1	PL-B2&M2
5	C1	C2	N/A	N/A

Details of abbreviations: Anterior leaflet (AL) strut chord attached to the lateral side of the leaflet (AL-S1) and both AL strut chords (AL-S2); Lateral AL marginal chords (AL-M1) and all AL marginal chords (AL-M2); Posterior leaflet (PL) basal chords attached to the lateral side of the leaflet (PL-B1) and all PL basal chords (PL-B2); Lateral PL marginal chords (PL-M1) and all PL marginal chords (PL-M2); All PL basal chords and lateral marginal chords (PL-B2&M1); All PL marginal chords and lateral basal chords (PL-M2&B1); All PL chords (PL-B2&M2); Anterolateral commissural chords (C1) and all commissural chords (C2). NA: Not applicable.

Table II: Descriptive statistics (mean \pm SD and median) of the pressure withstood by the intact valve and after severing of selected chordae tendineae.

Chords severed*	No. of specimens	Pressure withstood by intact valves (mmHg)		Pressure withstood by valves after cutting of chords (mmHg)		p-value ⁺
		Mean \pm SD	Median	Mean \pm SD	Median	
AL-S1	6	148 \pm 4	150	146 \pm 9	150	NS
AL-S2	6	148 \pm 4	150	142 \pm 12	148	NS
AL-M1	6	143 \pm 11	150	47 \pm 63	15	0.030
AL-M2	6	143 \pm 11	150	0 \pm 0	0	0.018
PL-B1	6	147 \pm 8	150	125 \pm 61	150	NS
PL-B2	6	147 \pm 8	150	123 \pm 61	149	NS
PL-B2&M1	6	147 \pm 8	150	100 \pm 75	145	NS
PL-M1	6	150 \pm 0	150	149 \pm 3	150	NS
PL-M2	6	150 \pm 0	150	141 \pm 21	150	NS
PL-M2&B1	6	150 \pm 0	150	70 \pm 54	68	0.018
PL-B2&M2	12	148 \pm 6	150	54 \pm 67	21	0.004
C1	6	145 \pm 12	150	76 \pm 46	62	0.030
C2	6	145 \pm 12	150	37 \pm 28	34	0.018

*Details of abbreviations (chords severed): Anterior leaflet (AL) strut chord attached to the lateral side of the leaflet (AL-S1) and both AL strut chords (AL-S2); Lateral AL marginal chords (AL-M1) and all AL marginal chords (AL-M2); Posterior leaflet (PL) basal chords attached to the lateral side of the leaflet (PL-B1) and all PL basal chords (PL-B2); Lateral PL marginal chords (PL-M1) and all PL marginal chords (PL-M2); All PL basal chords and lateral marginal chords (PL-B2&M1); All PL marginal chords and lateral basal chords (PL-M2&B1); All PL chords (PL-B2&M2); Anterolateral commissural chords (C1) and all commissural chords (C2).

⁺Wilcoxon signed rank test
NS: Not significant.

Severing all basal and marginal chords attached to the posterior leaflet had the greatest effect in reducing valve competence. In this case, valves withstood pressures of 54 \pm 67 mmHg (c.f. 148 \pm 6 mmHg for intact valves), which was significantly less than the pressure withstood by the intact valves. Figure 4 shows the posterior leaflet prolapsing after all basal and marginal chords attached to the posterior leaflet were severed; it was observed that the leaflets did not close properly.

Commissural chordae

Severance of the commissural chords significantly reduced mitral valve competence (see Table II). Severing all commissural chords reduced the pressures withstood by the valves to 37 \pm 28 mmHg (c.f. 145 \pm 12 mmHg for intact valves). Figure 5 shows that, during valve failure, a small segment at the edge of the anterior and posterior leaflets (where the two meet) prolapsed after the anterolateral commissural chords were severed.

Discussion

The role of chordae tendineae in mitral valve competence was investigated, with an experimental apparatus being used to apply static pressure to porcine

mitral heart valves with the chords intact, and also after selected chordal severing.

The study results confirmed earlier findings that the anterior leaflet marginal chords - but not the strut chords - are vital for valve competence (9-13). The severance of marginal chords significantly reduced the pressure withstood by the valves compared with intact valves, but there was no significant reduction in pressure when the strut chords were severed.

The anterior leaflet marginal chords (which insert at the edge of the leaflet) may allow the edge of the anterior leaflet to seal against the posterior leaflet, to help maintain valve competence. Severing anterior leaflet marginal chords allowed the edge of the leaflet to prolapse freely when pressure was applied to the valve, and so the valve did not prevent the leakage of fluid (Fig. 3b). Although the strut chords did not influence valve competence, it has been suggested that they have an important role in determining the function of the valve as a funnel (8). It has been found that severance of the strut chords increased movement of the lateral parts of the anterior leaflet, and that restriction of such movement of the anterior leaflet led to in-flow and out-flow funnels during diastole and systole, respectively.

Previous studies that used a beating heart either in a live animal (10,11,13) or after removal from an animal

(12) have the advantage that they allow the overall effect of rupture of chords on the function of the heart to be investigated. However, in-vitro testing allows careful control over experimental variables, unlike in-vivo experiments. In vivo, it may be difficult to isolate the effect of cutting chords from the other changes introduced, and there is no single simple measure of the effect of cutting a select group of chords on valve function. The method used in the present study had the advantage that it is easy to isolate the effect of severing selected chords and the failure pressure provides a simple measure of this effect. Furthermore, the method used allowed easy access and identification of chords, which is difficult in either a beating heart or a live animal, especially with regard to posterior leaflet chords.

Unlike the anterior leaflet, the marginal and basal chords that insert into the posterior leaflet do not seem to have well-defined roles. Valve competence was compromised when a combination of marginal and basal chords were severed. This may represent a mechanism that compensates for damage to a single chord or few chords. This would seem to make sense, as posterior leaflet chords have been found to tear at lower strains and loads than anterior leaflet chords (16). Rupture or elongation of posterior leaflet chords has been quoted as being the main reason for mitral valve repair (17). However, the present authors are not aware of any previous in-vivo or in-vitro studies which demonstrate that they have an effect on mitral valve function. It appears from the present results that the posterior leaflet chords are less important in preventing valve failure than the commissural chords or anterior leaflet chords. Clinically, posterior leaflet chordal rupture is known to cause mitral valve regurgitation, which presents the possibility that it may be the secondary changes (e.g. to the material properties of the valve leaflet) that occur to the valve that cause large mitral regurgitation, and not the chordal rupture on its own.

The severing of commissural chords significantly reduced the pressures that the valves could withstand, as leakage of fluid occurred between the edges of the valve leaflets. Commissural chords seal the edges between the anterior and posterior leaflets (where the two meet), and cutting them led to regurgitant fluid; this leakage from the valve prevented the pressure behind the valve from increasing. The regurgitation was due to the prolapse of small segments of leaflet tissue at the commissures between the two leaflets. Therefore, commissural chords have a role to seal the anterior and posterior leaflets together at the commissures during valve closure, thus preventing leakage through the mitral valve.

In conclusion, the chords of the mitral valve exhibit a hierarchy of importance in relation to valve competence. The most critical are the anterior leaflet marginal chords and commissural chords, whereas the anterior leaflet strut chords and posterior leaflet marginal and basal chords are less critical for mitral valve competence.

Acknowledgements

The authors thank EPSRC for a research studentship provided to D.M.E., and Grampian University Hospitals NHS Trust Endowment Research Fund for financial support.

References

1. Espino DM, Hukins DWL, Shepherd DET, et al. Determination of the pressure required to cause mitral valve failure. *Med Eng Phys* (in press) [UPDATE?]
2. Carpentier A. Cardiac valve surgery - the 'French correction'. *J Thorac Cardiovasc Surg* 1983;86:323-337
3. Galloway AC, Grossi EA, Bizakis CS, et al. Evolving techniques for mitral valve reconstruction. *Ann Surg* 2002;236:288-294
4. Maisano F, Torracca L, Oppizzi M, et al. The edge-to-edge technique: A simplified method to correct mitral insufficiency. *Eur J Cardiothorac Surg* 1998;13:240-246
5. Lim KO, Boughner DR. Mechanical properties of human mitral valve chordae tendineae: Variation with size and strain rate. *Can J Physiol Pharmacol* 1975;53:330-339
6. Kunzelman KS, Cochran RP. Mechanical properties of basal and marginal mitral valve chordae tendineae. *Am Soc Artif Intern Organs Trans* 1990;36:M405-M408
7. Lam JHC, Ranganathan N, Wigle ED, et al. Morphology of the human mitral valve 1. Chordae tendineae: A new classification. *Circulation* 1970;41:449-458
8. Goetz WA, Lim HS, Pekar F, et al. Anterior mitral leaflet mobility is limited by the basal stay chords. *Circulation* 2003;107:2969-2974
9. He S, Weston MW, Lemmon J, et al. Geometric distribution of chordae tendineae: An important anatomic feature in mitral valve function. *J Heart Valve Dis* 2000;9:495-501
10. Messas E, Guerrero JL, Handschumacher MD, et al. Chordal cutting: A new therapeutic approach for ischemic mitral regurgitation. *Circulation* 2001;104:1958-1963
11. Nielsen SL, Timek TA, Green GR, et al. Influence of anterior mitral leaflet second order chordae tendineae on left ventricular systolic function.

- Circulation 2003;108:486-491
12. Obadia JF, Cendrine C, Chassignolle JF, et al. Mitral subvalvular apparatus. Different functions of primary and secondary chordae. *Circulation* 1997;96:3124-3128
 13. Timek TA, Nielsen SL, Green R, et al. Influence of anterior mitral leaflet second order chordae on leaflet dynamics and valve competence. *Ann Thorac Surg* 2001;72:535-541
 14. Kunzelman KS, Cochran RP, Verrier ED, et al. Anatomic basis for mitral valve modeling. *J Heart Valve Dis* 1994;3:491-496
 15. Guyton AC, Hall JE. *Textbook of Medical Physiology*, 9th edn. WB Saunders, Philadelphia, 1996.
 16. Sedransk KL, Grande-Allen KJ, Vesely I. Failure mechanics of mitral valve chordae tendineae. *J Heart Valve Dis* 2002;11:644-650
 17. Grande-Allen KJ, Griffin BP, Calabro A, et al. Myxomatous mitral valve chordae. II: Selective elevation of glycosaminoglycan content. *J Heart Valve Dis* 2001;10:325-333