DISTANCE BETWEEN MITRAL ANULUS AND PAPILLARY MUSCLES: ANATOMIC STUDY IN NORMAL HUMAN HEARTS

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Background: Preservation of the annulo–papillary muscle continuity in mitral valve replacement is important. Even in patients who require excision of the mitral apparatus, the continuity can be restored. However, there is no guide to the proper length for the resuspension. **Methods:** In 57 normal cadaveric hearts, the distance from the tip of the papillary muscle to its corresponding mitral annulus was directly measured. **Results:** The distance from the tip of the anterolateral papillary muscle to the left trigone (10-o'clock position: D10) and to the point between the anterior and the middle scallops of the mural leaflet (8-o'clock position: D8) was 23.5 ± 3.7 mm and 23.2 ± 3.6 mm, respectively. The distance from the tip of the posteromedial papillary muscle to the right trigone (2-o'clock position: D2) and to the point between the middle and the posterior scallops of the mural leaflet (4-o'clock position: D4) was 23.5 ± 4.0 mm and 23.5 ± 3.9 mm, respectively. There was no statistically significant difference among the 4 distances ($P = .96$). Each distance was significantly longer than the corresponding chordae tendineae (D10 vs the anterior main chorda: 17.2 ± 3.9 mm, D8 vs the anterior cleft chorda: 14.5 ± 3.2 mm, D2 vs the posterior main chorda: 17.9 ± 4.3 mm, and D4 vs the posterior cleft chorda: 14.9 ± 3.2 mm, respectively; $P = .0001$). The mean distance had a significant correlation with the mitral annular diameter ($r = 0.31$, $P = .019$). **Conclusions:** In normal hearts, the annulo–papillary muscle distances of the mitral apparatus are similar in 2-, 4-, 8-, and 10-o'clock positions and correlate with the mitral annular diameter. (J Thorac Cardiovasc Surg 1999;118:636-41)

The importance of the continuity between the mitral annulus and the papillary muscle for left ventricular performance¹⁻⁵ and for prevention from postoperative mid-ventricular rupture^{6,7} in mitral valve replacement has been widely recognized. In case of mitral valve replacement for patients who require total excision of the leaflets and the chordae tendineae, mitral allograft⁸ or expanded polytetrafluoroethylene (ePTFE) sutures^{9,10} have been used to restore the annulo–papil-

lary muscle continuity. The proper length of the ePTFE sutures or allograft chordae for the resuspension, however, is difficult to determine. We describe an anatomic study of the distance between the mitral annulus and papillary muscles in 57 normal hearts for a guide to the resuspension procedure in mitral valve replacement.

Materials and methods

Fifty-seven consecutive human hearts were studied at autopsy. All of the subjects were Japanese aged 23 to 95 years (67.5 ± 11.3 years, mean $\pm$ standard deviation). The subjects included 38 men and 19 women. Body weights ranged from 24 to 75 kg (45.4 ± 10.9 kg) and the heights of the bodies ranged from 136 to 179 cm (158.1 ± 7.8 cm). Hearts with any evidence of valvular disease or ischemic heart disease were excluded from this study. The nomenclature of the mitral valve system was based on the report of Lam and associates¹¹ (Fig 1).

Immediately after the heart was taken from the body, the left atrium was excised to allow full visualization of the mitral valve. Without any ventriculotomy, the heart was placed on a wet gauze sheet loosely covering a well so that the heart was

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Fig 1. Mitral apparatus. ALPM, Anterolateral papillary muscle; PMPM, posteromedial papillary muscle; AoL, aortic leaflet; Ant.Com.L., anterior commissural leaflet; Post.Com.L., posterior commissural leaflet; Ant.Scal., anterior scallop; Mid.Scal., middle scallop; h, height of a leaflet; l, length of the attachment of a leaflet; Post.Scal., posterior scallop; Rt. Trigone, right fibrous trigone; Lt. Trigone, left fibrous trigone; 1, anterior main chorda; 2, posterior main chorda; 3, anterior paramedial chorda; 4, posterior paramedial chorda; 5, anterior paracommissural chorda; 6, posterior paracommissural chorda; 7, anterior commissural chorda; 8, posterior commissural chorda; 9, anterior cleft chorda; 10, posterior cleft chorda.

situated in the “gauze cradle” without any distortion of its shape. With gentle upward tension on the leaflets to straighten the chordae tendineae, the annulo–papillary muscle distances were measured with a caliper (with a metric rule graduated to 1 mm) in 4 directions according to our resuspension method.¹² The 2 distances were measured from the tip of the anterolateral papillary muscle to the annulus: to the left fibrous trigone (10-o’clock position) and to the point between the anterior and the middle scallops of the mural leaflet (8-o’clock position). Also, the 2 distances were measured from the tip of the posteromedial papillary muscle to the annulus: to the right fibrous trigone (2-o’clock position) and to the point between the middle and the posterior scallops of the mural leaflet (4-o’clock position) (Fig 2). We defined the “tip” of the papillary muscle as the point of insertion of the main chordae. Even in the hearts with a papillary muscle with multiple heads,¹³ the insertion of the main chordae at the papillary muscle was successfully located in this study. Then the left ventricle was incised along the lateral border to avoid damaging the papillary muscles. The mitral valve was cut through between the posterior commissural leaflet and the posterior scallop of the mural leaflet. The width and height of the leaflets and the length of the chordae tendineae were measured with a caliper. The mitral annular circumference was

calculated with the sum of the all attachments of the valves. Then it was divided by π to yield the mitral annular diameter. All measurements were accomplished before fixation of the hearts with 37% formaldehyde solution.

Data were analyzed with SPSS software package for Windows version 8.0 (SPSS Inc, Chicago, Ill). All results are shown as mean $\pm$ standard deviation. Comparisons of continuous variables in 4 annulo–papillary distances were performed by a 1-way analysis of variance, and significant differences were specified by Duncan’s multiple range test. Each annulo–papillary distance and the length of the corresponding chorda was compared by paired *t* test. Pearson’s correlation coefficients and simple regression were used to analyze the relationship between the mean distance and the mitral annular diameter, body surface area, and heart weight.

Results

Fig 3 illustrates the 4 annulo–papillary muscle distances and their corresponding chordae tendineae. The annulo–papillary muscle distances were similar in all 4 positions ($P = .96$, by 1-way analysis of variance). Each distance was significantly longer than the length of the corresponding chordae tendineae: the distance

Fig 2. Diagram of the annulo–papillary muscle distances that were measured in the study: 2-o'clock position, The annulus at the right fibrous trigone; 4-o'clock position, the annulus at the point between the middle and the posterior scallops of the mural leaflet; 8-o'clock position, the annulus at the point between the anterior and the middle scallops of the mural leaflet; 10-o'clock position, the annulus at the left fibrous trigone; ALPM, anterolateral papillary muscle; PMPM, posteromedial papillary muscle.

from the anterolateral papillary muscle to the 10-o'clock position versus the anterior main chorda (23.5 ± 3.7 mm vs 17.2 ± 4.1 mm), the distance from the anterolateral papillary muscle to the 8-o'clock position versus the anterior cleft chorda (23.2 ± 3.6 mm vs 14.5 ± 3.2 mm), the distance from the posteromedial papillary muscle to the 2-o'clock position versus the posterior main chorda (23.5 ± 4.0 mm vs 17.8 ± 4.7 mm), and the distance from the posteromedial papillary muscle to the 4-o'clock position versus the posterior cleft chorda (23.5 ± 3.9 mm vs 14.8 ± 3.1 mm) (all, $P = .0001$).

The mitral annular diameter ranged from 22.3 to 40.1 mm (29.7 ± 3.5 mm). The heart weight ranged from 150 to 490 g (307.5 ± 68.6 g). Body surface area ranged from 1.03 to 1.73 m² (1.38 ± 0.17 m²). There were weak but statistically significant correlations between the mean annulo–papillary muscle distances (23.5 ± 3.1 mm) and the mitral annular diameters ($r = .31$, $P = .019$) (Fig 4), the heart weights ($r = .36$, $P = .006$), and the body surface areas ($r = .31$, $P = .018$).

The other measurements of the mitral apparatus are described in Table I.

Discussion

The importance of annulo–papillary muscle continuity for global left ventricular function in prosthetic valve replacement for mitral regurgitation has been widely recognized.^{1–5} We have applied the concept of restoration of annulo–papillary muscle continuity in patients with mitral stenosis since 1984. Our clinical result showed that postoperative regional shortenings of the left ventricle were greater in patients who underwent chordal preserving mitral valve replacement than in patients with the conventional chordal severing procedure.¹² Although some controversy exists whether this method offers significant postoperative functional improvement for the patients with mitral stenosis, the preservation of the annulo–papillary continuity is still important to prevent transverse mid-ventricular disruption after mitral valve replacement.^{6,7} Even in patients with severe mitral stenosis who require resection of the whole valve leaflets and chordae tendineae, it is possible to restore the continuity by resuspending the papillary muscle to the mitral annulus either with mitral allograft⁸ or ePTFE sutures.⁹

One of the technical problems in restoration of annulo–papillary continuity with ePTFE sutures is how to determine the proper suture length. Although Frater¹⁴ described the anatomic rules of determining the length of the artificial chordae in the case of chordal replacement for mitral regurgitation, there could be no chordae tendineae available to assess the proper length of ePTFE sutures in severe mitral stenosis. The resuspension length of the papillary muscle is important. If it is too short, excessive tension might cause diastolic dysfunction or tissue disruption at the site of the ePTFE sutures.¹⁵ If too long, the ePTFE sutures cannot transmit enough tension during a cardiac cycle. To the best of our knowledge, none of the reports has described a proper method to determine the resuspension length.

We performed the present study to provide an anatomic reference for the resuspension procedure. We measured the papillary muscle resuspension length in normal cadaveric hearts instead of the hearts with mitral stenosis because of the lack of specimens. Before mitral valve operations, annulo–papillary muscle distance in patients with mitral stenosis might be shorter than that in the normal population. Gash and coworkers¹⁶ demonstrated reduced left ventricular end-diastolic volume index of patients with mitral stenosis compared with control subjects. We, however, think the annulo–papillary muscle distance measured in the normal hearts could be applicable for the heart with mitral stenosis at the time of mitral valve surgery, because left ventricular end-diastolic volume generally increases

Fig 3. Annulo-papillary muscle distance and the length of the corresponding chordae tendineae. *D10*, The distance from the tip of the anterolateral papillary muscle to the anulus at the left fibrous trigone; *AMC*, anterior main chorda; *D8*, the distance from the tip of the anterolateral papillary muscle to the anulus between the anterior and the middle scallops of the mural leaflet; *ACC*, anterior cleft chorda; *D2*, the distance from the tip of the posteromedial papillary muscle to the anulus at the right fibrous trigone; *PMC*, posterior main chorda; *D4*, the distance from the tip of the posteromedial papillary muscle to the anulus between the middle and the posterior scallops of the mural leaflet; *PCC*, posterior cleft chorda. * $P = .0001$ by paired t test. There was no statistical difference among the 4 distances ($P = .96$ by analysis of variance).

Fig 4. Distribution of the mean annulo-papillary muscle distances relative to the mitral annular diameters.

after successful percutaneous mitral valvuloplasty¹⁷ in which the native annulo-papillary muscle continuity has been preserved. The relevance of cadaveric heart to an arrested continuously perfused heart was not clear. However, Komeda and associates¹⁸ showed that the distance from the tip of the papillary muscle to the mitral annular plane was constant, regardless of cardiac cycle

and loading conditions. Therefore we believe the use of the cadaveric hearts for the measurement is valid.

Acar and associates⁸ directly measured the distance from the plane of the mitral anulus to the tip of the anterolateral papillary muscle (*D1*) and from that to the tip of the posteromedial papillary muscle (*D2*) in 82 human mitral allografts. They measured perpendicular

Table I. Measurements of mitral apparatus in normal hearts

	Present study	Carpentier ²⁰
Weight of the heart (g)	307.5 ± 68.6	340
Circumference (mm)	93.2 ± 11.0	116 ± 3.5
Aortic leaflet		
Attachment (mm)	32.0 ± 4.8	32 ± 1.3
Height (mm)	23.4 ± 2.9	23 ± 0.9
Main chordae		
Anterior (mm)	17.2 ± 3.9	19 ± 0.4
Posterior (mm)	17.9 ± 4.3	17 ± 0.2
Paramedial chordae		
Anterior (mm)	16.2 ± 3.7	15 ± 0.5
Posterior (mm)	16.8 ± 3.4	NA
Paracommissural chordae		
Anterior (mm)	15.5 ± 3.0	17 ± 0.3
Posterior (mm)	17.5 ± 4.0	NA
Mural leaflet		
Anterior scallop		
Attachment (mm)	14.1 ± 3.6	NA
Height (mm)	11.2 ± 2.3	9 ± 1
Middle scallop		
Attachment (mm)	19.3 ± 4.1	NA
Height (mm)	13.8 ± 2.9	14 ± 0.9
Posterior scallop		
Attachment (mm)	13.6 ± 3.3	NA
Height (mm)	11.0 ± 2.3	10 ± 1.2
Cleft chordae		
Anterior (mm)	14.5 ± 3.2	13 ± 3.7
Posterior (mm)	14.9 ± 3.2	13 ± 3.7
Anterior commissural leaflet		
Attachment (mm)	7.7 ± 2.1	12 ± 3.3
Height (mm)	8.7 ± 2.4	8 ± 1
Commissural chorda (mm)	12.3 ± 3.6	13 ± 0.2
Posterior commissural leaflet		
Attachment (mm)	7.2 ± 2.1	17 ± 0.8
Height (mm)	8.3 ± 2.0	8
Commissural chorda (mm)	13.8 ± 3.9	15 ± 0.05

NA, Not available.

distance between the plane and the papillary muscle tip, instead of an oblique distance from the tip to the anulus itself. They reported that D1 (21 ± 3 mm) was shorter than D2 (26 ± 4 mm). We did not find such a difference in this study. Although the posteromedial papillary muscle tends to be placed deeper in the left ventricle from the mitral annular plane than the anterolateral papillary muscle,¹⁹ there are variations. We and Carpentier and associates²⁰ did not find a significant difference in the lengths of the chordae tendineae between those from the anterolateral papillary muscle and those from the posteromedial papillary muscle (Table I); the lengths of these chordae tendineae could be different if the depth of the papillary muscle in the left ventricle was significantly different. Other possible explanations for the discrepancy could be due to the

different reference points of the mitral anulus to measure the distance. We measured the distances between the tip of the papillary muscle to the 2 corresponding points of the mitral anulus, which was not the same as those to the plane of the anulus. Also we measured the distance in vitro while applying gentle tension on the leaflets to straighten the chordae tendineae. This upward tension could minimize the difference, if any.

If annulo-papillary muscle continuity is to be restored with either ePTFE sutures or a mitral allograft in mitral valve replacement, preoperative or intraoperative determination of the distance between the tip of papillary muscle and the mitral anulus is crucial in each case, because of the anatomic variations of the papillary muscles such as position, number, shortening, or development. However, we think our anatomic findings can offer some guidance and the rule by which to determine the length for the procedure.

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REFERENCES

- Gams E, Schad H, Heimisch W, Hagl S, Mendler N, Sebening E. Preservation versus severance of the subvalvular apparatus in mitral valve replacement: an experimental study. *Eur J Cardiothorac Surg* 1990;4:250-6.
- Yun KL, Rayhill SC, Niczyporuk MA, Fann JI, Zipkin RE, Derby GC, et al. Mitral valve replacement in dilated canine hearts with chronic mitral regurgitation. *Circulation* 1991;84(Suppl):III112-24.
- Okita Y, Miki S, Kusuhara K, Ueda Y, Tahata T, Yamanaka K, et al. Analysis of left ventricular motion after mitral valve replacement with a technique of preservation of all chordae tendineae. *J Thorac Cardiovasc Surg* 1992;104:786-96.
- David TE, Uden DE, Strauss HD. The importance of the mitral apparatus in left ventricular systolic function after mitral valve replacement. *Circulation* 1986;68:76-82.
- Rozich JD, Carabello BA, Usher BW, Kratz JM, Bell AE, Zile MR. Mitral valve replacement with and without chordal preservation in patients with chronic mitral regurgitation. *Circulation* 1992;86:1718-26.
- Miller DW Jr, Johnson DD, Ivey TD. Does preservation of the posterior chordae tendineae enhance survival during mitral valve replacement? *Ann Thorac Surg* 1979;28:22-7.
- Spencer FC, Galloway AC, Colvin SB. A clinical evaluation of the hypothesis that rupture of the left ventricle following mitral valve replacement can be prevented by preservation of the chordae of the mural leaflet. *Ann Surg* 1985;202:673-80.
- Acar C, Tolan M, Berrebi A, Gaer J, Gouezo R, Marchix T, et al. Homograft replacement of the mitral valve: graft selection, technique of implantation, and results in forty-three patients. *J Thorac Cardiovasc Surg* 1996;111:367-80.
- David TE. Mitral valve replacement with preservation of chordae tendineae. *Saudi Heart J* 1990;1:32-6.
- Okita Y, Miki S, Ueda Y, Tahata T, Sakai T, Matsuyama K.

- Replacement of chordae tendineae using expanded polytetrafluoroethylene (ePTFE) sutures during mitral valve replacement in patients with severe mitral stenosis. *J Card Surg* 1993;8:567-78.
11. Lam JH, Raganathan N, Wigle ED, Silver MD. Morphology of the human mitral valve. I. Chordae tendineae: a new classification. *Circulation* 1970;41:449-58.
 12. Okita Y, Miki S, Ueda Y, Tahata T, Sakai T, Matsuyama K. Mitral valve replacement with maintenance of mitral annulopapillary muscle continuity in patients with mitral stenosis. *J Thorac Cardiovasc Surg* 1994;108:42-51.
 13. Ramsheyi S-A, Pargaonkar S, Lassau J-P, Acar C. Morphologic classification of the mitral papillary muscles. *J Heart Valve Dis* 1996;5:472-6.
 14. Frater RWM. Anatomical rules for the plastic repair of a diseased mitral valve. *Thorax* 1964;19:458-64.
 15. Komeda M, DeAndam A Jr, Glasson JR, Bolger AF, Nikolic SD, et al. Improving methods of chordal-sparing mitral valve replacement. Part II. Optimal tension for chordal resuspension. *J Heart Valve Dis* 1996;5:477-83.
 16. Gash AK, Carabello BA, Cepin D, Spann JF. Left ventricular ejection performance and systolic muscle function in patients with mitral stenosis. *Circulation* 1983;67:148-5.
 17. Liu CP, Ting CT, Yang TM, Chen JW, Chang MS, Maughan WL, et al. Reduced left ventricular compliance in human mitral stenosis: role of reversible internal constraint. *Circulation* 1992;85:1447-56.
 18. Komeda M, Glasson JR, Bolger AF, Daughters GT II, Ingels NB Jr, Miller DG. Papillary muscle-left ventricular wall "complex." *J Thorac Cardiovasc Surg* 1997;113:292-301.
 19. Rusted IE, Scheifley CH, Edwards JE. Studies of the mitral valve. I. Anatomic features of the normal mitral valve and associated structures. *Circulation* 1952;6:825-31.
 20. Carpentier A, Guerinon J, Deloche A, Fabiani JN, Relland J. Pathology of the mitral valve. In: Kalmanson D, editor. *The mitral valve*. London: Edward Arnold; 1976. p. 65-77.

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