CUTTING THE SECOND ORDER CHORDS DURING MITRAL VALVE REPAIR

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Abstract

The chordae tendinae connect the papillary muscles to the mitral valve. While the first-order chordae serve to secure the leaflets to maintain valve closure and prevent mitral valve prolapse, the second-order chordae are believed that they play a role in maintaining normal LV size and geometry. The papillary muscles, from where the chordae tendinae originate, function as shock absorbers that compensate for the geometric changes of the left ventricular wall. The second-order chordae connect the PMs to both trigons under tension. The tension distributed towards the second-order chordae has been demonstrate to be more than three-fold that in the first-order counterpart. Cutting the second-order chordae puts all the tension on the first-order chordae, that can go closer to their rupture point. However, it has been experimentally demonstrated that the tension where the first-order chordae break is 6.8 N, by far higher than the maximal tension reached, that is 0.4 N. Even if the clinical reports have been favorable, the importance of cutting the second-order chordae to recover curvature of the anterior leaflet and increasing the coaptation length between the mitral leaflet has been slowly absorbed by the surgical world. Nevertheless, there are progressive demonstrations that chordal tethering affects the anterior leaflet not only in secondary, but also in primary mitral regurgitation, having a not negligeable role in the long-term outcome of mitral repair.

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Abstract

The chordae tendinae connect the papillary muscles to the mitral valve. While the first-order chordae serve to secure the leaflets to maintain valve closure and prevent mitral valve prolapse, the second-order chordae are believed that they play a role in maintaining normal LV size and geometry. The papillary muscles, from where the chordae tendinae originate, function as shock absorbers that compensate for the geometric changes of the left ventricular wall. The second-order chordae connect the PMs to both trigons under tension. The tension distributed towards the second-order chordae has been demonstrate to be more than three-fold that in the first-order counterpart. Cutting the second-order chordae puts all the tension on the first-order chordae, that can go closer to their rupture point. However, it has been experimentally demonstrated that the tension where the first-order chordae break is 6.8 N, by far higher than the maximal tension reached, that is 0.4 N. Even if the clinical reports have been favorable, the importance of cutting the second-order chordae to recover curvature of the anterior leaflet and increasing the coaptation length between the mitral leaflet has been slowly absorbed by the surgical world. Nevertheless, there are progressive demonstrations that chordal tethering affects the anterior leaflet not only in secondary, but also in primary mitral regurgitation, having a not negligeable role in the long-term outcome of mitral repair.

The chordae tendinae (CT) are strong and fibrous connections between the papillary muscles (PMs) and the leaflets of the mitral valve (MV). Each PM provides CT to its closest half of the anterior and the posterior MV leaflets.

According to the insertion site, CT can be classified as leaflet, commissural or cleft CT. Leaflet CT insert at the border (first-order or marginal CT) or at the ventricular surface of the leaflet (second-order or basal CT), close to the rough zone. The basal CT that insert to the anterior leaflet (AL), if thicker and stronger than the others, are called strut chordae. Commissural and cleft CT are typically fan-shaped.

The CT, after their origin, divide in branches, usually 3 to 6. In general, one goes to the margin of the leaflet, another one to the border between the rough and the clear zone and a third one to the clear zone. The number of first order CT inserted to a single cusp is 22 and of second order CT is 10[1]. There are as well third-order chordae that arise from the wall of the left ventricle (LV) and insert exclusively into the posterior leaflet (PL).

CT are not vascularized. They convey blood to and from the leaflets in vessels coursing the length of their shafts, but the absence of branching vasculature suggests CT derive their nutrient supply by diffusion[2]. It is noteworthy to underline that neovascularization due to mechanical or hypoxic stress weakens the CT and is at the basis of chordal rupture[3].

Pathophysiology of chordae tendinae

The CT function to transmit the contractions of the PMs to the leaflets. The first-order CT serve to secure the leaflets to maintain valve closure and prevent MV prolapse. Their section causes acute mitral regurgitation (MR). On the contrary the section of the second-order CT does not produce MR and it is believed that they play a role in maintaining normal LV size and geometry. To perform these functions, the CT must contain a high degree of elasticity, as well as considerable strength and endurance. A study showed that CT are composed of multiple layers of elastic fibers, an inner collagen core, and an outer layer of endothelial cells (fig. 1)[4]. During stretching, when PM contraction straightens the chords, the collagenous

wavy pattern disappears and transfers the peak stress during contraction to the leaflets. The sleeve-shaped elastic network that surrounds the internal collagen suggests that on relaxation of tension, the elastic fibers would tend to restore the collagen to their wavy configuration.

From the mechanical point of view, the smaller chordae are less extensible than the larger ones[5]. Then marginal chordae are half as extensible as second-order chordae, over 4 times stiffer in the pre-transitional range, and 1.6 times stiffer in the post-transitional range, than second-order chordae[6]. The reason is that collagen fibrils are more highly crimped in ticker CT and hence have a smaller period, as supported by direct measurements[5].

CT are instrumental for the reciprocal exchange of force between the PMs, the mitral annulus and the fibrous skeleton. The PMs, anatomically and functionally distinct from the LV wall, function as shock absorbers that compensate for the geometric changes of the LV wall while maintaining their tips at a constant distance to their hemi-annulus[7]. Marginal chordae may be fundamental for leading edge control and for correct leaflet coaptation, but, since their shape and tension change continuously during the cardiac cycle, the mechanism responsible for maintaining constant this annulo-papillary distance relies on the second-order chordae, and in particular on the two, thick strut chordae of the AL, that, for their characteristics, can support this annulo-papillary distance. The AL collagen fibers are oriented from the insertion of the strut chords toward the fibrous trigons, in direction of the load. This suggest that the strut chordae connect the PMs to both trigons under tension. The tension distributed towards the second-order chordae has been demonstrate to be more than three-fold that in the first-order counterpart[8]. The correct distribution of the tension does not make the mitral annulus distance vary during the cardiac cycle, while the apex to mitral annulus distance changes significantly at the expense of the changes in the apex to papillary muscle tips[7].

Cutting the second order chordae

Tethering of the second-order chordae has been recognized as one of the most important mechanisms at the basis of the onset and of worsening of secondary MR. Moreover its persistence is recognized as the cause of failure of isolated mitral reductive annuloplasty (MRA) (fig. 2). Transection of the second-order chordae has been proposed by Messas et al[9] as an adjunct to MRA to improve leaflet coaptation and to reduce MR return. However, even if introduced in 2001, there is no general agreement on the efficacy of this technique.

The curvature of the leaflets is designed to reduce the stress on the leaflets during the cardiac systole. The presence of tethered second-order chordae eliminates the curvature and increases the stress on the leaflet. Salgo et al[10] demonstrated, in a finite study, that, compared with a flat leaflet, 10% curvature reduced leaflet stress by 100% from 335 to 3 MPa. However, cutting the second-order chordae from one side recovers curvature, but on the other side transfers the tension on the first-order chordae, that now have to face a tension higher than usual. The risk of rupture of first-order chordae under excess of tension and the role of the second-order chordae in maintaining the annulo-papillary stability and LV geometry, casted a shadow on the benefit that chordal cutting (CC) could provide, especially due to controversial experimental results. The positive results obtained by Messas et al[9,11,12] were questioned by other experimental works[13-17], that showed impairment of the LV function after CC. However, the first clinical reports, appeared in 2005[18,19], showed good results and no reduction in LV function after a follow-up of 6 months and 2 years, respectively. Furthermore, Fayad et al[19]identified an aortotomy as the best surgical approach for CC, because of the optimal access to the ventricular side of the AL. In an observational comparative study, Borger et al[20] showed that, at 2-year follow-up, MR return was reduced in the CC group with improved ejection fraction (EF) by +10%. Our group, in a propensity matched study, reported, at a follow of 35 months. reduced MR in the CC group with increased EF (from 31% to 40%)[21], showing the safety of the procedure. Nevertheless, CC is slowly absorbed by the surgical community, still concerned about possible harmful effects of the technique.

We postulate that the role of the second-order chordae is different in a heart with previous acute myocardial infarction and ischemic MR than in a normal heart. In a normal setting, the second-order chordae, connecting the PMs to the trigones through their insertion to the MV leaflets, absorb the tension generated by the PMs themselves. By their insertion into the MV leaflets, they contribute to reduce the peak systolic stress.

In a pathologic situation, the second-order chordae, which insert on the AL, being tethered, eliminate its curvature, increasing the systolic peak stress by 100-fold[10]. By cutting the second-order chordae, the AL recovers its curvature, reducing the systolic peak stress by 100-fold, but now the transmission of the systolic stress falls completely on the first-order chordae. In an experimental setting, Padala et al[22] found that, displacing the PMs in three different directions (apically, apico-laterally and apico-lateral-posteriorly), the tension on the marginal chordae, compared to the basal values, increased more on the right-sided (till 4.6-fold) than on the left-sided chordae (till 2.1-fold) and were generally lower when the PMs were displaced apically and higher when displaced apico-lateral-posteriorly. When the anterior second-order chordae were cut, the increase of tension, compared with basal values, was respectively till 7.3-fold for the right-sided and till 3.7-fold for the left-sided marginal chordae. Then the tension on marginal chordae increases with PMs displacement, with a further increase after CC. As the first-order chordae are stiffer but less elastic than the second-order chordae, the increased tension can bring the marginal chordae closer to the rupture point. However, in experimental settings, the measured forces supported by the first-order chordae of the AL after CC were not higher than 0.4 N[22,23], significantly smaller than the failure load of 6.8 N required for rupture of the anterior marginal chordae reported by Sedransk et al[24]. The risk of rupture of the marginal chordae seems then to be only theoretical, and anyway overwhelmed by the benefits (recover of the AL curvature and improvement of the coaptation).

When to cut the second-order chordae

There is no specific indication for CC reported in the literature. Borger et al[20] divided the second-order chordae to the AL, PL and commissure that arose from the PM(s) affected by the infarcted myocardium. Patients in the CC group had lower ejection fraction and larger hearts. Our group[21] included only patients who had an AL banding angle <145° using, as a surgical approach, an aortotomy. However, the revival of the concept of MV remodelling and the surgical implications consequent to this concept[25-28], let us think to a different role for the CT in originating and maintaining leaflets tethering, more dynamic than previously supposed.

When MR starts, because of PM displacement and chordal tethering or other causes, a set of adaptations termed 'mitral plasticity' is initiated within the MV that serves to reduce the amount of regurgitation. This goal is achieved by an increase of the length and of the area of the leaflets and of the length of the CT. This adaptation to mechanical stress, induced by MR of any origin, is sustained by endothelial-to-mesenchimal transition (EndMT) and matrix remodelling, which facilitates leaflet growth[27], mediated by transforming growth factor β (TGF-β). The plasticity is said to be 'balanced' if the MV remains competent or with mild regurgitation despite left ventricular dilation and PM displacement, and 'unbalanced' if, despite adaptation, significant MR develops[27,29]. The MV increases its dimensions but histological remodelling is more pronounced than in a balanced response and the valve becomes fibrotic, stiff, less distensible, thick and can shorten later because of the presence of scar-forming cells[30,31]. CT become stiffer, less extensible, fibrotic and can reduce their length. Of particular interest for MV remodelling is the activation of renin–angiotensin system after MI, as angiotensin II can trigger TGF-β expression[32], enhancing the profibrotic effects on the MV. Similar changes at the level of the CT further restrict leaflet movements.

Stress induced mitral plasticity and the resulting MV remodelling is a mechanism present in MR of any aetiology. Experimentally, it was demonstrated that MR, created by making a hole in the PL, was able to induce AL remodelling[33]. Moreover, tethering of the second-order chordae have been demonstrated in patients with prolapse of the PL[34,35] and prolapse or chordal rupture of the AL[36].

Surgical implications

The concept of CC was addressed since the beginning to secondary MR, where chordal tethering was one of the most evident generating causes. However, even if excess of chordal tethering was considered a possible contraindication to MV repair, once accepted the concept of CC, the problem is to decide when CC has to be performed. In other words, is it necessary to cut always the second-order chordae or only in selected cases? This is an impossible question to answer. We can only speculate that the presence of chordal tethering is

a possible cause of failure of MV repair, both in secondary and in primary MR, as causes at the basis of tethering are not only mechanical, but include metabolic changes that can make the process continue with time[36].

In primary MR chordal tethering is a well known risk factor for MR return after repair for PL prolapse[34,35]. Then our advice is to cut the second-order chordae even if tethering is mild, irrespective from the leaflet that prolapse (fig. 3 and 4).

In case of secondary MR, chordal tethering is an uncontrolled variable that affects the long-term result. CC improves AL mobility, which favors coaptation. We think that in presence of unbalanced mitral plasticity (short AL and tethered chordae) we have to reproduce surgically what was the goal of plasticity, that is a long AL and elongated chordae. This procedure, by us called surgical mitral plasticity[37], includes the augmentation of the AL and CC. When the AL is long enough to assure a good coaptation and the chordae are tethered, we prefer to cut them through an aortotomy (fig. 5). Persistence of chordal tethering after MRA is a risk factor for MR return (fig. 2).

The role of CC in MV repair, both primary and secondary, is not yet well defined. The suboptimal results of isolated MRA advice to expand the repair to valvular or subvalvular levels. CC, however, has not been included in any guideline, then its application depends on surgeon's choice. The clinical experience in secondary MR, even if limited, since today is favourable, demonstrating a reduction of MR return without any negative effect on LV function. The marginal chordae are subjected to increased tension when PMs displace and, after CC, the further increase of tension is not enough to cause chordal rupture (the values of tension measured experimentally are 15- to 20-fold lower than the tension of rupture). The application of CC in primary MR is still episodic, but the adverse predictive effect of preoperative chordal tethering in prolapsing leaflets has been well studied in the literature.

CC is an effective and reproducible strategy that addresses an anatomical aspect that represent an uncontrollable variable (fig. 6) that can only worsen the surgical results.

LEGEND

Fig. 1 – (A) Scanning electron micrograph of external aspect of the endothelial cells of the chorda, obtained from a 23-year-old subject (×3170). (B) The elastic fibers, situated underneath the endocardium which was removed (×1720). (C) Interior of a split chorda. Waves of collagen fibrils with similar dimensions (10.7 μm) to the reflections shown in (A) and undulations in (B) (×3260).

From Millington-Sanders et al.[4], with permission.

Fig. 2 – Failure after isolated restrictive mitral annuloplasty for ischemic MR. (A) Transthoracic echocardiography. The AL is short (21 mm) and tethered (red arrow) and is not able to coapt with the PL. There is moderate MR. (B and C) Transoesophageal echocardiography. There is a significant tenting volume, which pushes the mitral valve inside the left ventricle. The AL has reduced mobility and cannot coapt with the PL due to chordal tethering.

MR, mitral regurgitation; AL, anterior leaflet; PL, posterior leaflet.

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Fig. 3 – Primary mitral regurgitation due to PL prolapse. Transoesophageal echocardiography. (A) There is wide PL prolapse, with a short (22 mm) and tethered (red arrow) AL. (B and C) The tethered portion of the AL is in the A3 area (red arrow), seen from the atrial and ventricular side. (D) After surgery, the PL prolapse was corrected, positioning the PL in a vertical position and the AL was augmented with a pericardial patch. Its length increased to 32 mm, with a coaptation length of 10 mm and a mean gradient of 1.5 mmHg.

PL, posterior leaflet; AL, anterior leafelt.

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Fig. 4 – Primary mitral regurgitation due to AL chordal rupture. Transoesophageal echocardiography, 2D and 3D reconstruction. There is a severe mitral regurgitation due to chordal rupture of AL (A). There is a tethering of the AL second-order chordae (arrow, A, B). The correction included use of artificial chordae and second-order chordae cutting. The AL recovered its normal shape (C).

AL, anterior leaflet.

Fig. 5 – Patient with severe dilated cardiomyopathy. (A) Severe mitral regurgitation, with a long AL and tethering of the second-order chordae (B, red arrow). Three-dimensional reconstruction of mitral annulus and leaflets in systole. (C) The AL is moved toward the apex and the second-order chords are tethered (red arrow). (D) After mitral annuloplasty and second-order cutting through aortotomy, the AL coapts with the posterior leaflet with a coaptation length of 9 mm. Chordal tethering disappeared.

AL, anterior leaflet.

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Fig. 6 – Transthoracic echocardiography. A, Preoperative: AL prolapse and mild second-order chord tethering (arrow). B, at discharge: no MR, but still a mild second-order chord tethering (arrow). C, after 6 months: moderate to severe MR due to AL prolapse with increased second-order chord tethering (arrow). Transoeasphageal 3D reconstruction of the mitral annulus and the mitral valve leaflets. D and E, the AL is attracted toward the apex (arrow). F, second-order chord tethering, previously mild, became severe (arrow). The attraction toward the apex prevents AL coaptation with the posterior leaflet, pushing the AL tip into the left atrium.

AL, anterior leaflet; MR, mitral regurgitation; 3D, three-dimensional.

From Calafiore et al[36]. with permission.

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