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Experimental Study / Deneysel Çalışma

Mechanical and physiological effects of indentational chords in sliding leaflet plasty technique: an *ex vivo* bovine heart model

Sliding yaprakçık plasti tekniğinde "indentational" kordaların mekanik ve fizyolojik etkileri: Ex-vivo sığır kalbi modeli

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ABSTRACT

Background: In this model of mitral valve repair simulation, we aim to analyze the mechanical and physiological effects of primary chords supporting the intentionally closed indentations in sliding leaflet plasty of the posterior leaflet of mitral valve.

Methods: Posterior quadrangular resection and sliding leaflet techniques were simulated in 24 cases in bovine heart. In all cases, posterior mitral leaflet indentations were closed with 5-0 silk sutures. The indentational chords were left untouched in group 1 (n=12), and were resected in group 2 (n=12). The coaptation lines between anterior and posterior leaflets were assessed in both groups. Presence of tethering chords in posterior leaflet was investigated while the mitral valve competence was tested under the pressure of 170 cmH_2O (125 mmHg).

Results: While coaptation lines were asymmetric in all cases in group 1, no asymmetric coaptation line was detected in group 2 ($p<0.001$). It was determined that the asymmetric coaptation lines in group 1 were caused by the primary chords supporting the intentionally closed indentations during the procedure.

Conclusion: It can be suggested that after closing the indentations, the primary chords supporting these indentations function as secondary chords which restrain leaflet mobilization in sliding posterior leaflet technique.

Keywords: Bovine heart model; mitral indentation; mitral valve repair simulations; primary chord.

ÖZ

Amaç: Bu mitral kapak tamiri simülasyon modelinde, mitral kapak posterior yaprakçık çentiklerinin sliding yaprakçık plasti tekniği sırasında kapatılması durumunda çentikleri destekleyen primer kordaların mekanik ve fizyolojik etkilerinin araştırılması amaçlandı.

Çalışma planı: Posterior kuadrangüler rezeksiyon ve sliding yaprakçık tekniği 24 olguda sığır kalbinde simüle edildi. Tüm olgularda, posterior mitral yaprakçık çentikleri 5-0 ipek dikiş ile kapatıldı. Grup 1'de (n=12) çentikleri destekleyen primer kordalara dokunulmadı, grup 2'de (n=12) ise çentikleri destekleyen primer kordalar rezeke edildi. Anterior ve posterior yaprakçıklar arasındaki koaptasyon hatları her iki grupta değerlendirildi. Mitral kapak yetkinliği 170 cmH_2O (125 mmHg) basınç altında test edilirken posterior yaprakçıkta gerginlik yapan korda varlığı araştırıldı.

Bulgular: Grup 1'deki tüm olgularda koaptasyon hatları asimetrik iken grup 2'de asimetrik koaptasyon hattı tespit edilmedi ($p<0.001$). Grup 1'deki asimetrik koaptasyon hatlarına uygulama sırasında kapatılan çentikleri destekleyen primer kordaların yol açtığı tespit edildi.

Sonuç: Çentikler kapatıldıktan sonra bu çentikleri destekleyen primer kordaların sliding posterior yaprakçık tekniğinde yaprakçık mobilizasyonunu kısıtlayan sekonder kordalar gibi işlev gördüğü iddia edilebilir.

Anahtar sözcükler: Sığır kalbi modeli; mitral çentik; mitral kapak tamiri simülasyonu; primer korda.

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Vast numbers of studies have been written concerning mitral valve replacement surgery,[1,2] but in Turkey, not many have focused on mitral valve repair surgery.[3] Simulation models have great importance, especially in resident education, since they offer them an opportunity to practice valve repair and improve their existing repair techniques. With few exceptions,[4-6] the simulation models documented in the literature are insufficient, particularly in the context of mitral valve repair surgery. However, our simulation model, which has been previously described in detail elsewhere,[7] makes it possible to simulate the state of the cardioplegic arrest period in the heart.

The posterior leaflet of the mitral valve in our model is inserted approximately two-thirds of the way up on the annulus, and the free edge is usually divided into three scallops by two indentations (sometimes improperly called clefts) that are supported by indentational chords (Figure 1).[8] However, in some cases, it is preferable to close the indentation in order to avoid separation, and this is especially in sliding leaflet plasty. Another reason for closing the indentation is to decrease the height of the posterior leaflet by creating a curtain effect. This approach, which allows for the coaptation line to be closer to the posterior annulus, is particularly helpful for treating systolic anterior motion. Sliding leaflet plasty is primarily indicated for cases involving systolic anterior motion and extensive leaflet prolapse. In this technique, it is necessary to resect all secondary chords close to the edge of the detached leaflet remnants to facilitate “sliding” after the quadrangular resection of the posterior leaflet.[9]

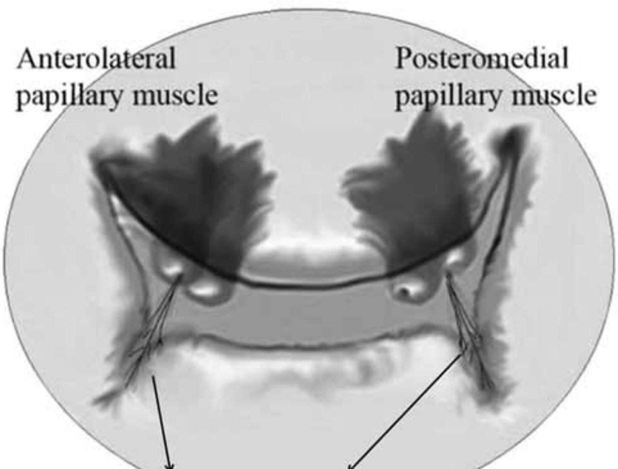

Figure 1. Indentations and their supporting chordae tendineae.

The rules that usually apply in sliding leaflet plasty procedure should be strictly obeyed in routine practice. This goal of this study was to analyze and identify the underlying mechanisms of the asymmetric coaptation line as well as the tethering over the posterior leaflet, both of which can be easily observed when performing this technique.

MATERIALS AND METHODS

This study was approved by the local hospital ethics committee. Isolated, fresh bovine hearts were obtained from a slaughterhouse and selected based on the intact state of the left ventricles. Approximately 50% of these hearts were suitable for the experiments, with the others being excluding due to the mitral valve, left ventricular wall, or ventricular septum injuries. The hearts and the mitral valves were then tested by mounting them on a study table (Figure 2). Ultimately 24 bovine hearts without any structural injuries were used for our *ex vivo* model. Before performing the sliding leaflet plasty technique, nerve hooks were used to carry out a valve analysis starting from the P1

Figure 2. The surgical table with two atrial retractors mounted on two rods is shown. It features the capability of three-dimensional movement to stabilize the bovine heart. The aortic valve leaflets were removed, and the aorta was connected to a water-filled tubing system. The top of the water-filled column was open to the atmosphere, and the height of this column was approximately 170 cmH_2O, which is equal to 125 mmHg.

scallop. In all of the cases, the quadrangular resection and posterior sliding leaflet technique was performed. In order to avoid the separation of the scallops from the posterior leaflet, the indentations were closed with interrupted 5-0 silk sutures. In addition the chordae tendineae supporting the indentations were preserved in the first 12 cases (group 1) but resected in the remaining 12 (group 2).

Ex vivo isolated heart model[7]

The *ex vivo* heart model consisted of a bovine heart and a study table (Figure 2). The table included three main parts: a pressure system to test the valve competence under 170 cmH_2O (=125 mmHg), green dressing, which was designed to cover the heart to avoid ventricular overdistention, and two atrial retractors, each capable of moving in three dimensions, which were designed for stabilization and valve exposure.

Although bovine hearts are not identical to human hearts, they have the same anatomical structures, including anterior and posterior leaflets, two papillary muscles, primary and secondary tertiary chords, and a mitral annulus. The posterior leaflets are usually divided into three segments (the P1, P2, and P3 scallops) by two indentations. The most important factor is that both hearts work with the same mechanical and physiological principles, making it possible to simulate the state of the heart's cardioplegic arrest period.

Study protocol

The aortic cusps were first resected, and the pressure system was then connected to the aorta. The heart was tested under static pressure to reveal any structural injury that might have occurred at the slaughterhouse, and the valve analysis was performed. Next, the indentations were marked with stay sutures (Figure 3a) and then closed with interrupted 5-0 silk

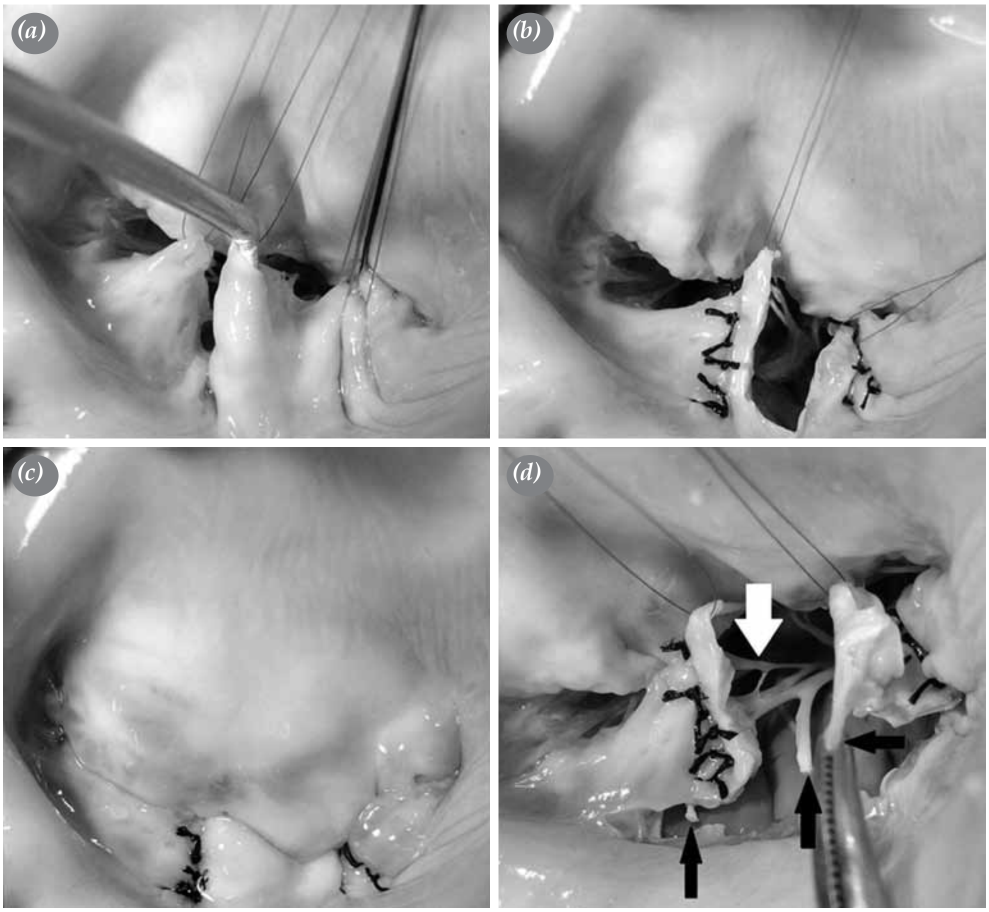

Figure 3. (a) Indentations marked with stay sutures. **(b)** Closed indentations with interrupted 5-0 sutures. **(c)** A quadrangular resection measuring approximately 15 mm in width was created in the P2 scallop. **(d)** The black arrow shows the secondary chords that were resected to facilitate leaflet mobility. Note that chords of the indentations, which acted as secondary chords after closing the indentation, were preserved on the side of the P1 scallop (white arrow).

sutures (Figure 3b). Both the P1 and P3 scallops were then detached from the posterior annulus, and the quadrangular resection width on the P2 scallop of the posterior leaflet was 15 mm in all of the experiments (Figure 3c). Afterwards, the primary chords supporting the indentations were preserved in group 1 (Figure 4a, white arrow) but resected in group 2. In addition, all of the secondary chords of the detached P1 and P3 scallops were also resected to facilitate leaflet mobility in both groups (Figure 3d and 4a, black arrows). Three posterior annular plicating sutures were then used in each case to decrease the posterior annular circumference (Figure 4b), and the repair process was completed using the sliding leaflet technique. At the end of each instance of mitral valve competence, the valve geometry and coaptation line between the anterior and posterior leaflet were evaluated under a static pressure of 170 cmH_2O (=125 mmHg).

In the evaluation process, the coaptation scores were given based on whether the valve was competent or not (0 points if it was not competent). If the valve was competent, then we determined whether the coaptation line was parallel to the posterior annulus. (1 point if not parallel and 2 points if parallel). After that, the posterior annular sutures were removed to analyze the subvalvular apparatus in both groups. After this, the indentational chords in group 1, which had been preserved in group 1, were resected, and the posterior leaflets were sutured to the posterior annulus. Subsequently, the mitral valves were reevaluated under static pressure.

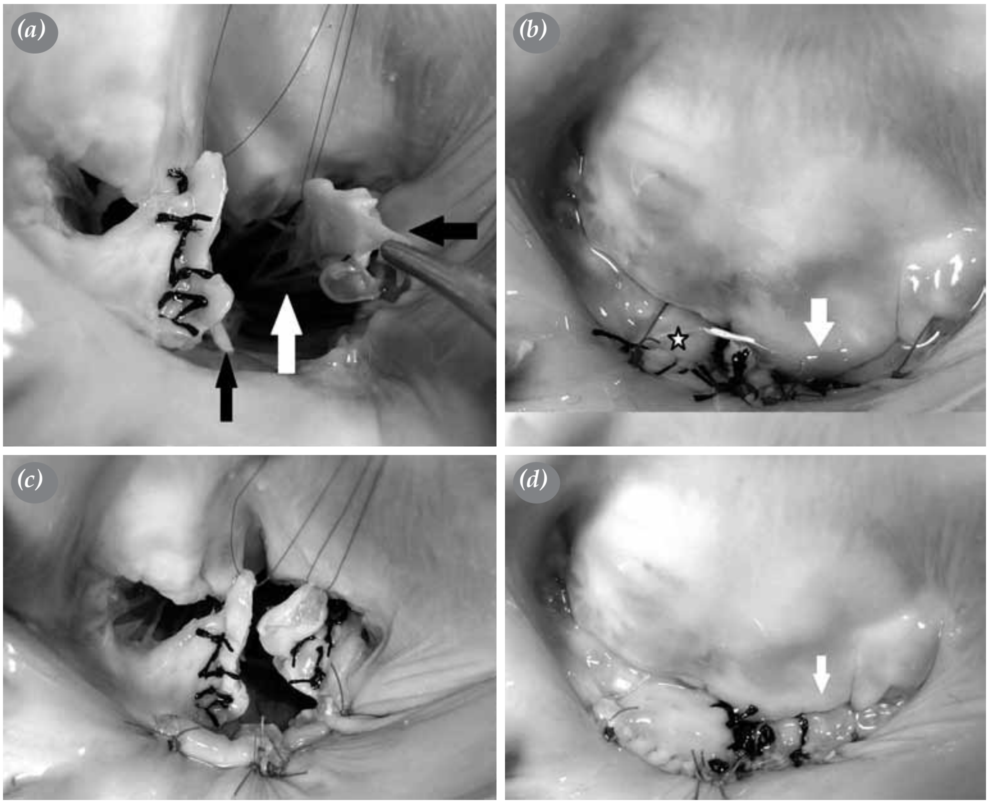

Figure 4. (a) The black arrows show the resected secondary chords. The white arrow indicates the primary chords of the indentations that were preserved on the side of the P3 scallop. **(b)** Annular compressing sutures were used to reduce the posterior annular circumference. **(c)** The white arrow shows the asymmetric closure line in group 1, which corresponded to the P3 scallop after the repair. This line was caused by the preserved chords that were supporting the closed indentations. The discordant height of the posterior leaflet in the asymmetrical and symmetrical (asterisk) coapting segments can also be seen. **(d)** The white arrow shows the symmetric closure line of the mitral valve after the resection of all of the primary indentational chords between P1 and P2 . Once the problem of the posterior annular suture line was solved, the chords were resected, and the posterior annular suture line was restored. Note that after resecting the chords in Figure 4c, the symmetrical coaptation line, which should be parallel to the posterior annulus, was restored.

Statistical analysis

Statistical analyses were performed using the SPSS Statistics for Windows version 17.0 (SPSS Inc., Chicago, IL, USA) software program. The parameters between independent groups were compared using with the Mann-Whitney U test, and statistical significance was set at a p value of <0.05.

RESULTS

We found that the mitral valves were competent and that the coaptation lines were parallel to the posterior annulus (symmetric coaptation line) in all of the cases in group 2. However, the coaptation lines were not parallel in group 1 (asymmetric coaptation line). Furthermore, two incompetent cases were observed postoperatively in the first evaluation (the mean coaptation score was 0.9±0.4 in group 1 and 2±0 in group 2; p<0.001).

Assessment of the asymmetric coaptation line in group 1

After removing the posterior suture lines, the subvalvular apparatus indicated that the cause of the asymmetric coaptation line was the chordae tendineae, which were supporting the indentations that had been preserved prior to the surgery and pulling them to the corresponding papillary muscle. Moreover, due to the tethering, the mean height of the asymmetrical coapting segments (Figure 4c) was smaller than the symmetrical coapting segments (Figure 4c) in the posterior leaflet (13.7±1.1 mm vs. 3.5±1.0 mm; p<0.05) because the tethering chords supporting the closed indentation were pulling the posterior leaflet down into the left ventricle in the coapting segments that were asymmetrical.

After the chords of the indentations were resected in group 1, the asymmetric coaptation lines and posterior leaflet height were normalized (Figure 4d); thus, symmetric coaptation lines were achieved. Moreover, the coaptation scores in group 1 and 2 were now similar (2±0 vs. 1.8±0.4; p=0.15), and the two cases with mitral insufficiencies in group 1 were also corrected. In addition, the discordant height between the symmetrical and asymmetrical coapting segments in the posterior leaflet was resolved (p=0.653).

Assessment of the symmetric closure line in group 2

Resecting the indentational chordae tendineae before suturing them initially resulted in increased leaflet mobility with no tethering chords. However, removing the indentational chords led to the appearance of a symmetric coaptation line.

Assessment of the mitral insufficiency in group 1

Although, tethering was observed in all cases in group 1 under static pressure, only two of them had regurgitation. The reason for this was not only attributable to the tethering. The hypoplasia that was identified in the P1 scallop in the first case and the P3 scallop in the second case were also responsible. These two cases had also double indentations at the contralateral side. Therefore, when the hypoplasia was present in the P1 or P3, the contralateral indentational chords caused more tethering than usual by acting as secondary chords after they were sutured. Therefore, when the supporting indentational chords were resected in the second evaluation, we then slid the leaflet over slightly, which caused the mitral insufficiency to disappear.

DISCUSSION

The functional characteristics of the mitral valve apparatus components should be investigated thoroughly to improve the success rates of repair techniques, and it is for this reason that research has been carried out using various simulation models. Rabbah et al.[10] evaluated the hemodynamic results of the edge-to-edge repair technique using a left-sided heart simulator. Similarly, Padala et al.[11] used a simulation model in their study entitled, "Effect of anterior strut chordal transection on the force distribution on the marginal chordae of the mitral valve". Furthermore, Poglajen et al.[12] utilized an *ex vivo* left ventricular model that simulated functional/ischemic mitral regurgitation with independent variations of annular size, papillary muscle position, and transvalvular pressure. In addition, successfully performed bench repairs of donor mitral valves before heart transplant procedures have also presented in the literature.[13-15] In the light of this scientific data, it is also possible to design simulation models for anatomical or physiological studies with an eye toward the surgical techniques involved in mitral valve repair surgery, and that was the goal of our experimental model which used an *ex vivo* heart under static pressure.

The indentations of the posterior leaflet are normal anatomical structures that allow the leaflet to fully open during diastole.[8] Perier[16] analyzed indentations between the P1 and P2 and the P2 and P3 and found that if they were deep, they could interfere with the goal of transforming the posterior leaflet into a smooth and regular vertical buttress. In a natural mitral valve, these indentations allow the posterior leaflet to expand

and follow the diastolic dilation of the annulus without tension on the free edge. However, because the annulus is fixed to the systolic position by the implantation of an annuloplasty ring, these indentations can no longer serve their physiological purpose and may even cause residual leaks. Accordingly, when the indentations are deep, it may be desirable to suture them with a 5-0 monofilament running suture to ensure a perfect result.[16]

In order to perform the sliding leaflet technique without annular plication, it is accepted that the gap between the two leaflet remnants in the posterior leaflet should be equal to or greater than 20 mm.[9] However, in our study, this technique was implemented after only a 15 mm gap had been created because it could have otherwise been concluded that excessive leaflet resection caused the asymmetric coaptation line and tethering chords. Therefore, we limited the resection width to 15 mm. The chords supporting the closed indentations resulted in tethering when they were not resected, and the contralateral indentational chords caused more tethering because the contralateral leaflet segment required more sliding than usual, especially in the hypoplastic segments in the P1 or P3 scallop.[9] Hence, these chords stretched the median suture line and decreased the height of the posterior leaflet in the asymmetrical coapting segments. This not only led to the asymmetric coaptation line between the anterior and posterior leaflet, but it also increased the coaptation depth in the asymmetrical coapting segments of the posterior leaflet. In spite of the posterior translocation of the coaptation line, if the height of the anterior leaflets was sufficient, no regurgitation leaks were observed. However, when the height was insufficient, as in the two cases in group 1, a posteriorly directed regurgitant jet flow can be seen.

We realized that after closing the indentation of the posterior leaflet, mobilizing the leaflet remnant in and of itself was not enough to avoid separation between the scallops even if the secondary chords were resected because new secondary chords were created when the indentations were closed. In other words, after closing the indentation, the supporting chords acted as secondary chords that restricted leaflet mobility.

Another decision that must be made is whether or not to decrease the posterior annular circumference. If this is deemed necessary, then the next question concerns whether the transverse compression sutures or vertical plication sutures are the most appropriate.[9] In this study, we chose the first option. However, we determined that transverse compression sutures were not as effective for decreasing the posterior annular circumference.

Our experimental model also allowed for the observation of the most common lesions found in cases involving fibroelastic deficiency. The two main forms of degenerative mitral valve disease are fibroelastic deficiency and Barlow's disease,[17] but these are both completely different from each other. The lesions associated with Barlow's disease have excessively thick and billowing leaflet segments, chordal elongation and rupture, calcification of the papillary muscles and/or an annulus with chordae restriction, and severe annular dilatation with giant valves.[17] In contrast, patients with mitral regurgitation due to fibroelastic deficiency lack the connective tissue that triggers leaflet and chordal thinning, which can eventually lead to chordal rupture.[9,17] As opposed to patients with excessive tissue, extensive leaflet resection or complex leaflet remodeling procedures are rarely indicated for those with fibroelastic deficiency.[9,17] In general, a limited quadrangular or triangular resection or simple leaflet resuspension with a chordal transfer or artificial chord is all that is required to correct the leaflet prolapse. Unlike cases with Barlow's disease, a normal bovine heart does not have any excess leaflet tissue, which is frequently seen in fibroelastic deficiency. Keeping this in mind, this study may provide a model for the lesions observed in patients with fibroelastic deficiency when posterior leaflet prolapse is present.

One of the limitations of our study was that we used bovine hearts because they can be easily procured and are similar in structure to human hearts.[7] However, none of the bovine hearts used in our model were diseased, and there was no annular dilatation. In addition, bovine hearts are normally larger than human hearts, but in our experimental model, the final state after repair compensates for this anomaly, which eliminates this potential limitation. Furthermore, while the non-beating flaccid bovine heart used in our model could not precisely mimic the functions of a mitral valve, it did adequately imitate the state of the arrested left ventricle after cardioplegia. Therefore, we believe that our model displays most of the features that surgeons experience during saline testing. Moreover, analyzing the mitral valve under a static pressure of 125 mmHg revealed the inadequacy of the surgical techniques that have been previously implemented. Now that the theoretical thought process has been validated by simulation studies such as ours, the next step is to use an *in vivo* model to try and replicate the results obtained from the *ex vivo* model.

Conclusion

After suturing the indentation, resecting the chords that were supporting them may further increase leaflet mobility, especially in valves which have no excess tissue. However, to evaluate the dynamic mechanical and physiological effects of the posterior sliding leaflet technique, the procedure should be further investigated using *in vivo* animal studies.

Declaration of conflicting interests

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REFERENCES

1. Keçeligil HT, Demirağ MK, Ersoy G, Bahçıvan M, İriz E, Kolbakır F ve ark. St. Jude medikal kapak protezi ile mitral kapak replasmanı: 179 hastaya ilişkin 10 yıllık deneyim. Turk Gogus Kalp Dama 1999;7:303-8.
2. Gürbüz A, Akel S, Işık Ö, İpek G, Dikmengil DM, Sezer H. Mekanik protez kapaklar ile mitral kapak replasmanı: Orta dönem klinik sonuçları. Turk Gogus Kalp Dama 1994;2:16-9.
3. Onan B, Erkanlı K, Onan İS, Ersoy B, Aktürk İF, Bakır İ. Clinical outcomes of mitral valve repair: a single-center experience in 100 patients. Turk Gogus Kalp Dama 2014;22:19-28.
4. Joyce DL, Dhillon TS, Caffarelli AD, Joyce DD, Tsirigotis DN, Burdon TA, et al. Simulation and skills training in mitral valve surgery. J Thorac Cardiovasc Surg 2011;141:107-12.
5. Yamauchi H, Vasilyev NV, Marx GR, Loyola H, Padala M, Yoganathan AP, et al. Right ventricular papillary muscle approximation as a novel technique of valve repair for functional tricuspid regurgitation in an ex vivo porcine model. J Thorac Cardiovasc Surg 2012;144:235-42.
6. Tavlasoglu M, Jahollari A, Amrahov A, Sahin MA. An instrument facilitates mitral valve repair training at home. Eur J Cardiothorac Surg 2012;41:940-1.
7. Tavlasoglu M, Durukan AB, Arslan Z, Kurkluoglu M, Amrahov A, Jahollari A. Evaluation of skill-acquisition process in mitral valve repair techniques: a simulation-based study. J Surg Educ 2013;70:318-25.
8. Carpentier A, Adams DH, Filsoufi F. Mitral Valve Reconstruction, Chapter 5. Surgical Anatomy and Physiology. In: Carpentier's reconstructive valve surgery. Missouri: Saunders; 2010. p. 33.
9. Carpentier A, Adams DH, Filsoufi F. Mitral valve reconstruction. Chapter 11. Techniques in Type II posterior leaflet prolapse. In: Carpentier's reconstructive valve surgery. Missouri: Saunders; 2010. p. 115-26.
10. Rabbah JP, Siefert AW, Spinner EM, Saikrishnan N, Yoganathan AP. Peak mechanical loads induced in the in vitro edge-to-edge repair of posterior leaflet flail. Ann Thorac Surg 2012;94:1446-53.
11. Padala M, Gyoneva L, Yoganathan AP. Effect of anterior strut chordal transection on the force distribution on the marginal chordae of the mitral valve. J Thorac Cardiovasc Surg 2012;144:624-633.e2.
12. Poglajen G, Harlander M, Gersak B. Ex vivo study of altered mitral apparatus geometry in functional mitral regurgitation. Heart Surg Forum 2010;13:E172-6.
13. Prieto D, Antunes P, Antunes MJ. Donor mitral valve repair in cardiac transplantation. Transplant Proc 2009;41:932-4.
14. Massad MG, Smedira NG, Hobbs RE, Hoercher K, Vandervoort P, McCarthy PM. Bench repair of donor mitral valve before heart transplantation. Ann Thorac Surg 1996;61:1833-5.
15. Pawale A, Tang GH, Milla F, Pinney S, Adams DH, Anyanwu AC. Bench mitral valve repair of donor hearts before orthotopic heart transplantation. Circ Heart Fail 2012;5:e96-7.
16. Perier P. A new paradigm for the repair of posterior leaflet prolapse: respect rather than resect. Oper Tech Card Thorac Surg 2005;10:180-93.
17. Anyanwu AC, Adams DH. Etiologic classification of degenerative mitral valve disease: Barlow's disease and fibroelastic deficiency. Semin Thorac Cardiovasc Surg 2007;19:90-6.