Strain Distribution of the Leaflet of Monocusp Patch Measured by the Sonometrics System

Wentao Feng [a], Meng Guo [b] and Li Wang [c]

School of Biological Science and Medical Engineering, Beihang University, Beijing 100191, China.

[a]Fengwnt@qq.com, [b]madfrog88@qq.com, [c]459038090@qq.com

Abstract

Using a monocusp patch to treat congenital heart diseases is one of the most distinctive surgical procedures but the long-term availability and durability of the leaflet of monocusp is unsatisfactory. The strain distribution is important mechanical factor to study the mechanism of calcification and fatigue failure of the leaflet. To study the strain distribution of the leaflet is signality for improving its durability and long-term availability. This study measured and calculated the strain distribution by using sonometrics system and the results showed that the strain at the side of upper leaflet and the button of leaflet were larger than other region, the high strain areas were the risk part of calcification and fatigue failure.

Keywords

Monocusp; Sonometrics system; Strain distribution.

1. Introduction

Right ventricular outflow tract (RVOT) obstrction is a common symptom in tetralogy of Fallot and other complex congenital heart diseases. Using a transannular patch to enlarge RVOT is one of the most distinctive surgical procedures, but it leads to transvalvular regurgitation. Acute pulmonary valve regurgitation can lead to right ventricular (RV) dilatation and failure, tricuspid regurgitation, impaired exercise performance and arrhythmias [1,2], and seems to be associated with increased perioperative mortality [3]. To prevent pulmonary regurgitation, various techniques have been applied such as valved homograft patch or monocusp patch with different results [4,5]. Theoretically, a monocusp patch can reduce patch-related pulmonary regurgitation, but the long-term availability and durability is unsatisfactory, especially in younger children.

The stress and strain distribution are important mechanical factors to study the mechanism of calcification and fatigue failure of the leaflet. High stress area can lead to fatigue failure but the precise mechanism by which calcification occurs remains unclear. However, studies show that the calcification may be exacerbated by the stiffness of the valve and/or increased mechanical strain [6,7]. Therefore, to study the stress and strain distribution of the leaflet is signality for improving its durability and long-term availability.

This study measured and calculated the strain distribution by using sonometrics system. Sonomicrometry (Sonometrics Corporation, Ontario, Canada), as applied to biomedical research, is the measurement of distances within soft tissue by using sound energy. The measure method can be as small as possible interference to the object to be measured and the precision is high enough to measure the small strain of leaflet.

2. Method

2.1 Monocusp patch leaflet

The configuration of monocusp leaflet is usually shown in Fig. 1. The length of a and b are the main parameters of leaf shape. As a preliminary study on the strain measurement of monocusp leaflet, we chose the ratio of a and b is 2:3 as the research object. The monocusp used in this study was made of bovine pericardium, which is also used as the heart valve material.

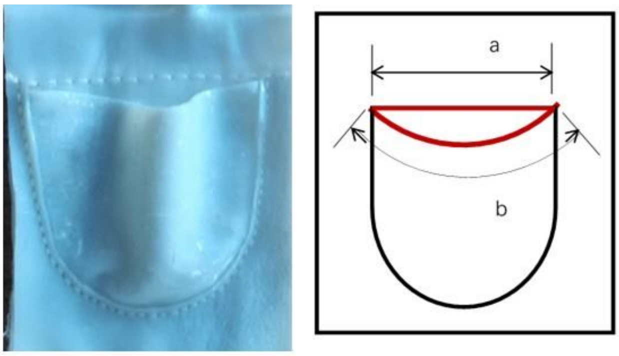

Fig. 1 Configuration of monocusp leaflet

2.2 Sonometrics system

Sonomicrometry (Sonometrics Corporation, Ontario, Canada), as applied to biomedical research, is the measurement of distances within soft tissue by using sound energy. Small piezoelectric crystals perform the task of transmitting and receiving short pulses of ultrasonic energy. These crystals are embedded, sutured, or otherwise fixed to the endpoints of the distances to be measured. One transducer generates a burst of sound as a transceiver and the other transducer receives this signal as a receiver. The time of sound wave traveling from the transceiver to the receiver is measured in sonomicrometry. The speed of sound in soft tissue is well characterized and the distance between two transducers is calculated as Velocity*Time. Actually each transducer can be used as both receiver and transceiver since it is possible to alter the function of some of all of the crystals.

When more than 3 transducers are used in experiments, sets of distance measurements can be converted into 3D coordinates. At first, four transducers are used to define a local coordinate system. The first one transducer is defined as the origin of the coordinate system. The second transducer is used to define X axis with the first transducer. Then with the third transducer, the XY plane is defined. The fourth one is used to set the positive Z direction. After XYZ axis set up, every other transducer position is defined in this local coordinate system. In this research, sonometrics system will be used to measure coordinate of specific points on the monocusp leaflet under different pulmonary arterial pressure conditions.

2.3 Measurement process

A total of 15 sensors were arranged, of which 4 were used to construct the coordinate system, and the other 11 were uniformly sewn on the leaflet and the suture line, as the marker points to outline the shape of the leaflet, as shown in Fig. 2. Then the patch was attached to a pipe with an internal diameter of 20 mm and the pipe was assembled into a steady back flow test system that produces a stable back pressure. The steady back flow test system was shown in figure 3. The back pressure was rised from 5 mmHg to 40 mmHg gradually to simulated right heart pressure environment. The distance data of sensors were measured at the reverse pressure of 5 mmHg, 10 mmHg, 20 mmHg, 30 mmHg and 40 mmHg.

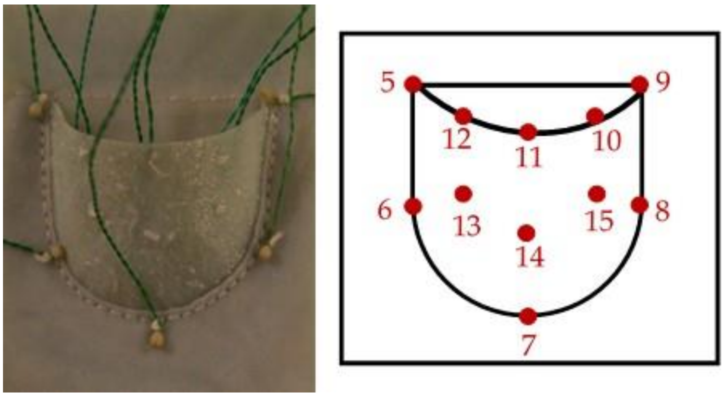

Fig. 2 sensors fixed on the leaflet

According to the measured distance data, the coordinates of each point were reconstructed, and the coordinate information of each mark point is obtained. Quadratic rational B spline is used to interpolate the leaflet, and the leaflet surface function at any time is defined as:

$$s(u,v)=\frac{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}P_{i,j}}{\sum_{i=0}^{n}\sum_{j=0}^{m}N_{i,p}(u)N_{j,q}(v)w_{i,j}}\quad 0\le u,v\le 1$$

$N_{i,p}(u)$ is the interpolation basis function at u direction. $N_{j,q}(v)$ is the interpolation basis function at v direction. $W_{i,j}=1$ is the weight of the control points. Pi,j is the coordinates of the (1，j) point.

The spatial coordinates of the mark points (Mij) are used as the interpolation points of the surface to establish equation:

$$S(u_i,v_j)=M_{ij}$$

Solution $P_{i,j}$, and any point position of the surface can be obtained.

Using Green strain to describe the strain. The step of calculating the Green strain at any point on the surface is calculated as follow,

First, calculate the covariant vector in the surface before deformation,

$$\mathbf{e}_i=\frac{\partial R(u_i)}{\partial u_i}\qquad i=1,2$$

e_i is the inverter vector, to meet:

$$\boldsymbol{e}^i\cdot\mathbf{e}_j=\begin{cases}1, i=j\\0, i\neq j\end{cases}$$

The metric tensor before deformation is:

$$G=g_{ij}\boldsymbol{e^i}\boldsymbol{e^j}$$

The covariant components of the metric tensor after deformation is :

$$g'_{ij}=\mathbf{e'}_i\cdot\mathbf{e'}_j$$

The Green strain tensor is:

$$E=\frac{1}{2}\left(g'_{ij}-g_{ij}\right)\boldsymbol{e^i}\boldsymbol{e^j}$$

The principal strain can be calculated according to the Green strain tensor.

3. Results

The strain distribution of leaflet under different pressures relative to 5 mmHg pressure is shown in Fig. 3. The results showed that the strain increased with the increase of pressure. the strain at the side of upper leaflet and the button of leaflet were larger than other region, the high strain areas were the risk part of calcification and fatigue failure.

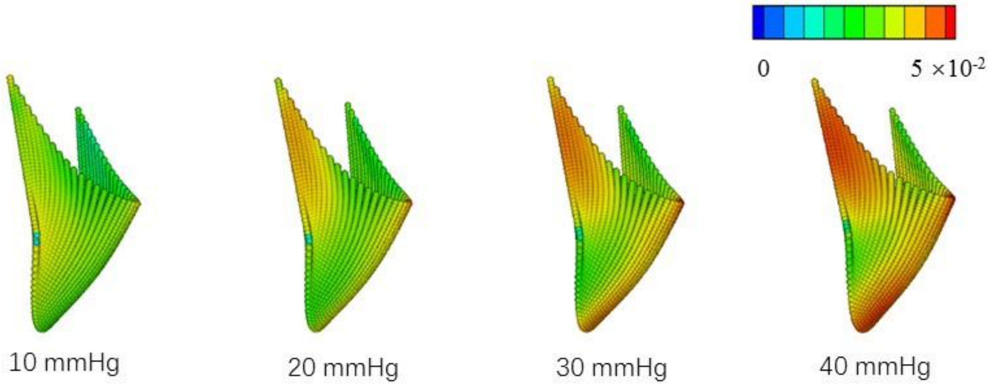

Fig. 3 Strain distribution of leaflet under different pressures

4. Discussion

Monocusp patch is one of the most commonly used surgical implants in the treatment of right ventricular outflow tract stenosis. However, the main problem of monocusp patch is the poor long-term availability and durability caused by calcification. The major factor affecting the calcification of leaflet is the strain. This study measured and calculated the strain distribution by using sonometrics system and analyzed the effect of strain distribution on leaflet.

The measurement of the strain of leaflet is very difficult, because the leaflet is very soft, and the measurement of contact will affect the mechanical state of the leaflet. At present, the 3D imaging method is more commonly. In this method, markers were made on the leaflet, then two cameras were taken into a certain angle to shoot the markers. The space position of each marker can be calculated and then the strain is calculated. Howere, this method required high transparency and zero optical distortion of the experimental section, which is difficult to achieve for complicated flow channel. The sonomicrometry system is not limited in this area.

In this study, we only analyzed the patch of one kind of configuration of monocusp leaflet. Other configurations of monocusp need to be measured in the future. Moreover, the steady back flow is not the same as the physiological pulsatile flow, the strain distribution of leaflet at pulsatile flow should be measured to obtain more accurate results.

5. Conclusion

In this study, the sonomicrometry system was used to measure the strain distribution of the monocusp leaflet. The strain of the upper side and the bottom of the leaflet was found to be larger than other parts.

References

[1] E.L. Bove, R.E. Kavey, C.J. Byrum, et al. Improved right ventricular function following late pulmonary valve replacement for residual pulmonary insufficiency or stenosis, Journal of Thoracic & Cardiovascular Surgery, vol. 90(1985):50-55.

[2] J.S. Carvalho, E.A. Shinebourne, C. Busst, et al. Redington AN. Exercise capacity after complete repair of tetralogy of Fallot: deleterious effects of residual pulmonary regurgitation, Br Heart J, vol. 67(1992):470—3.

[3] Y. Naito, T. Fujita, H. Manabe, et al. The criteria for reconstruction of right ventricular outflow tract in total correction of tetralogy of Fallot, Journal of Thoracic & Cardiovascular Surgery, vol. 80(1980):574-81.

[4] F.J. Macartney, O. Scott, M.I. Ionescu. Late hemodynamic results of fascia lata reconstruction of the right ventricular outlet, American Heart Journal, vol. 89(1975):195.

[5] D.F. Dickinson, D.I. Hamilton. Reconstructing of the right ventricular outflow tract using an inlayed aortic root homograft, European Journal of Cardiology, vol. 10(1979):331-343.

[6] L. Osman, M.H. Yacoub, N. Latif, et al. Role of human valve interstitial cells in valve calcification and their response to atorvastatin, Circulation, vol. 114(2006):547-52.

[7] M.E. 3Rd, M.K. Chawla, A.W. Chang, et al. Identification and characterization of calcifying valve cells from human and canine aortic valves, Journal of Heart Valve Disease, vol. 8(1999):254.