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Altered stresses and dynamics after single and double annuloplasty ring for aortic valve repair

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Key question

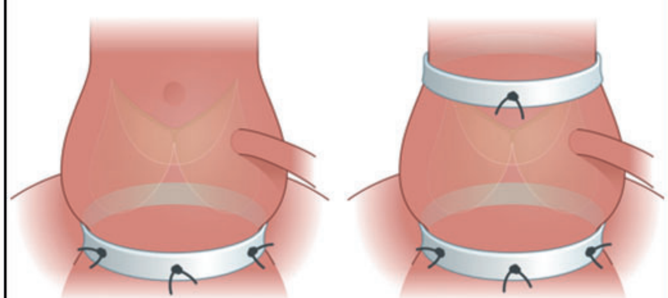
Is double ring annuloplasty better than single ring for aortic root stabilization?

Key finding(s)

Radial stresses and expansion are reduced at the sinotubular junction with the double ring compared with the single ring.

Take-home message

The double ring technique is better at stabilizing the aortic root, which should be considered when performing aortic valve repair.



Abstract

OBJECTIVES: Aortic valve repair procedures for the treatment of isolated aortic valve insufficiency may be improved by stabilizing the functional aortic annulus using a double annuloplasty ring at the aortic annulus and sinotubular junction (STJ). The objective of this study was to compare the geometrical changes and aortic root stress distribution when using a single subvalvular ring and a double sub- and supravalvular ring *in vivo*.

METHODS: Both the single- and double-ring procedures were performed successively in nine 80-kg pigs. Measurements were performed intraoperatively using sonomicrometry crystals in the aortic root to evaluate geometrical changes and annular and STJ force transducers measuring the segmental radial stress distribution.

RESULTS: The total force in the STJ was significantly reduced after the double-ring procedure from 1.7 ± 0.6 to 0.04 ± 1.1 N (P = 0.001). The double-ring procedure significantly reduced the STJ area from 234.8 ± 37.6 to 147.5 ± 31.8 mm^2 (P = 0.001) and expansibility from 17 ± 6% to 8 ± 3% (P = 0.001). With the single-ring procedure, the STJ shape was circular but became more oval with the double-ring procedure. The double-ring procedure did not affect stress distribution or geometry in the aortic annulus.

CONCLUSIONS: The double-ring procedure stabilized the whole aortic root by reducing radial stress distribution in the STJ more efficiently than the single-ring procedure. Both area and expansibility were reduced with the double-ring procedure. These results confirm the importance of addressing the entire functional aortic annulus for optimal aortic valve repair procedures.

Keywords: Aortic annulus • Aortic valve repair • Dacron ring annuloplasty • Double-ring annuloplasty • Dynamic characterization • Aortic insufficiency

ABBREVIATIONS

ECC	Extracorporeal circulation
LN	Left/non-coronary segment
LR	Left/right-coronary segment
LV dP/dt	Time derivative of left ventricular pressure
MD	Mid-diastole
MS	Mid-systole
NC	Non-coronary sinus
RN	Right/non-coronary segment
STJ	Sinotubular junction

INTRODUCTION

For patients with isolated aortic valve insufficiency and aortic annulus dilatation, aortic valve repair has proven superior to conventional valve replacement [1, 2]. A risk factor for recurrent aortic insufficiency after aortic valve repair is a dilated aortic annulus >25 mm that is not stabilized with a subvalvular annuloplasty ring [3–5]. When a subvalvular annuloplasty ring is used in aortic valve repair, it reduces annulus diameter, increases coaptation height and enhances freedom from recurrent aortic insufficiency [6–8]. The severity of aortic insufficiency has been related to the degree of dilatation at the level of the aortic annulus but also the sinotubular junction (STJ) [4]. When a dilatation occurs at the aortic annulus or STJ, the normal STJ/annulus ratio is distorted and entails reduced cusp coaptation and subsequently aortic insufficiency. Lansac *et al.* [3] have shown that a double annuloplasty ring procedure with an annuloplasty ring at both the aortic annulus and STJ tends to reduce the degree of recurrent aortic insufficiency compared with a single annuloplasty ring at the aortic annulus. This approach supports the concept of considering the aortic root as a functional aortic unit, referred to as the functional aortic annulus [9], where all structural components must be addressed to achieve optimal results after aortic valve repair.

Several aortic annuloplasty rings exist for aortic valve repair. The 2 most commonly used are the polytetrafluoroethylene suture annuloplasty and the Dacron ring obtained from a Dacron tube graft (Vascutek, Terumo, Japan). Both the Dacron ring and the suture annuloplasty have shown good results with and without the remodelling procedure [3, 10–12]. Some concerns exist regarding the expansibility of the Dacron ring, because the Dacron tube graft material is thought to have a limited capacity of radial expansion. The suture annuloplasty is considered to be more compliant than the Dacron ring, but the placement of the suture annuloplasty is less standardized.

To enhance the understanding of the mechanisms behind a potentially more durable aortic root repair, a systematic, reproducible and controllable investigation must be performed to compare the biomechanical properties of the single-ring versus the double-ring repair procedure.

We hypothesized that the double annuloplasty ring procedure stabilizes the entire aortic root more than the single annuloplasty procedure with preserved expansibility, and reduced stresses in all segments of the STJ.

Hence, the aim of this porcine *in vivo* study was to compare:

- The segmental force distribution in the aortic annulus and STJ after the single-ring and double-ring procedures.
- The overall dimensions, shape and segmental expansion of the aortic annulus and STJ after the single-ring and double-ring procedures.

MATERIALS AND METHODS

Ten female 80 kg pigs (Mixed Duroc and Landrace–Yorkshire) comprised the study material. One could not be weaned from extracorporeal circulation (ECC), resulting in 9 datasets available for analysis. The following 2 surgical groups were compared: single subvalvular annuloplasty ring versus double sub- and supravalvular annuloplasty ring. To minimize biological heterogenicity, both procedures were tested on the same animal, thus each animal acted as their own control. The study complied with Danish guidelines for animal research and was approved by the Danish Inspectorate of Animal Experimentation, no. 2013-15-2934-00915.

Force measurements

Two dedicated force transducers with 3 measuring arms were inserted; 1 in the aortic annulus and 1 at the STJ. At the aortic annulus, the force transducer was implanted intraluminally with each arm located upstream of the leaflet commissures in the interleaflet triangle, as previously described [13, 14]. At the STJ, the force transducer was implanted externally on the aortic root, with the arms located downstream of the STJ (Fig. 1A). The force transducers measured radial forces in 3 individual segments corresponding to the 3 interleaflet triangles at the aortic annulus and the STJ, i.e. the left/right-coronary (LR), right/non-coronary (RN) and left/non-coronary (LN) segment at each level. The transducer comprised a basal ring and 3 equidistantly placed vertical arms with a diameter of 20 and 19 mm, respectively. On each arm, 2 strain gauges formed a Wheatstone half-bridge. The force transducers measured strain corresponding to radial

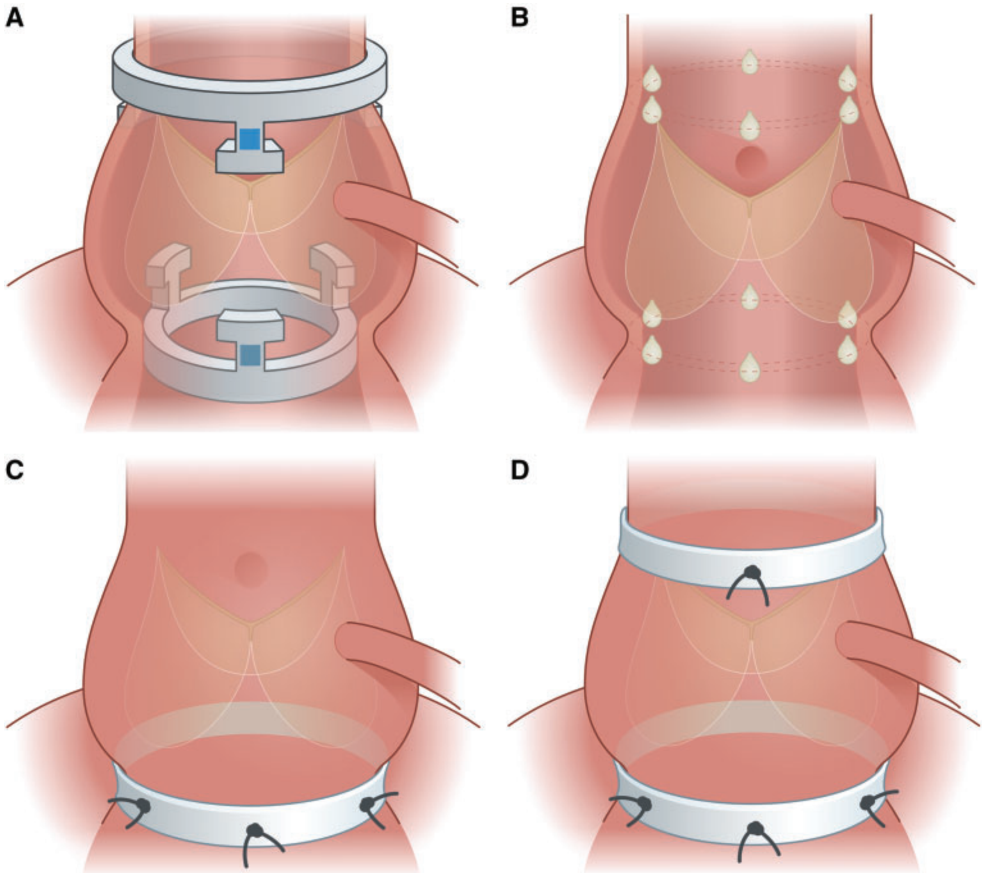


Figure 1: Schematic illustration of the implanted force transducers, sonomicrometry crystals and annuloplasty procedures. (**A**) The 2 force transducers with 3 measuring arms placed internally at the aortic annulus and externally at the sinotubular junction. (**B**) The aortic root with the positioning of the 12 sonomicrometry crystals. (**C**) Single subvalvular ring annuloplasty at the aortic annulus. (**D**) Double sub- and supravalvular ring annuloplasty at the aortic annulus and sinotubular junction. Modified from Benhassen *et al.* [15].

compression and distension at each level. Prior to each experiment, the force transducers were calibrated to convert strain into calibrated forces. These forces described the segmental radial stress distribution at each level.

Geometrical measurements

For geometrical assessment, we implanted 2-mm sonomicrometry crystals (Sonometrics Corp., London, ON, Canada): 6 at the aortic annulus and 6 at the STJ (Fig. 1B). The crystals were placed with 1 crystal at each nadir and 1 crystal at each commissure, at the respective level (Fig. 2). The sonomicrometry method has been validated and described in detail in earlier porcine studies [14–17].

Surgical protocol

Transportation, medication and handling of the animals have previously been described [15, 18]. After sternotomy, corporal circulation and cardioplegic arrest, the aortic valve was exposed through a transverse aortotomy 2 cm downstream of the STJ.

The annular annuloplasty was sized to obtain a mild to moderate downsizing of the aortic annulus diameter of 10–15% in systole, which corresponded to a 22-mm Dacron ring [15], and a 20-mm Dacron ring at the STJ was used to complete the double-ring procedure. A standardized approach was used for the 2 annuloplasty procedures (Fig. 1C and D). For the single-ring procedure, an open ring of Dacron tube graft with a height of 4 mm and a diameter of 22 mm was used. The Dacron ring was anchored with 6 U-stitches around the aortic annulus to fasten the ring in the subvalvular position as described by Lansac *et al.* [19]. Due to the close proximity of the left coronary artery to the myocardium in the pig, it was not possible to position the ring under the left main coronary artery. The ring was opened and anchored closely at each side of the left coronary artery with U-stitches. For the double-ring procedure, we used an additional Dacron ring at the STJ, with a height of 4 mm and a diameter of 20 mm [3]. The Dacron ring was secured with 3 U-stitches above each sinus, and was closed by one of the anchoring U-sutures, to ensure that the ring was circumferential. The aorta was closed using running 4–0 Prolene® sutures. Mikro-Tip pressure catheters (SPR-350, Millar Instruments, Houston, TX, USA) were placed in the left ventricle through the apex and the ascending aorta through the aortotomy. After reperfusion, weaning off ECC and haemodynamic stabilization, data collection was performed for 20 s, with the acquisition of simultaneous pressure, force and electrocardiogram (ECG) data for both groups. Hereafter, the force transducers were released and removed to acquire simultaneous pressure, geometrical and ECG data without influence from the transducers for both groups. See the flowchart of the experimental protocol in Fig. 3. Two-dimensional echocardiography (Vivid I, GE Vingmed Ultrasound AS, Horten, Norway) was performed to verify valve competence at baseline, and after single- and double-ring implantation. The animals were euthanized

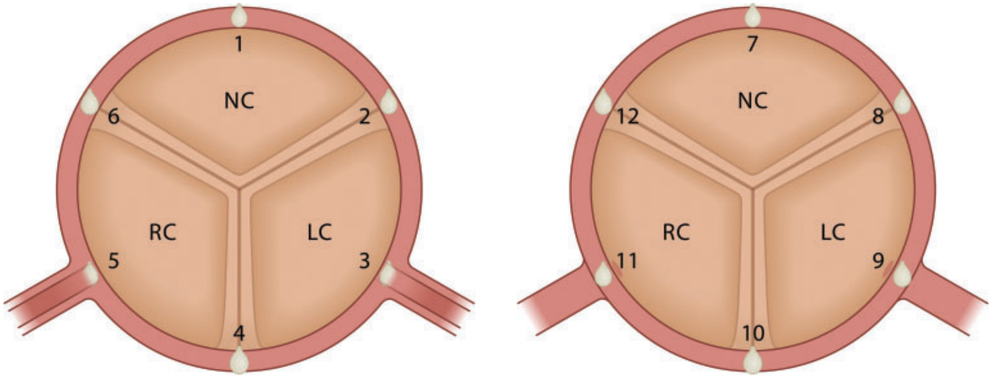


Figure 2: Schematic illustration of the position of the sonomicrometry crystals at the 2 levels of the aortic root. Left: aortic annulus; Right: sinotubular junction. LC: left coronary sinus; NC: non-coronary sinus; RC: right coronary sinus. Modified from Benhassen *et al.* [15].

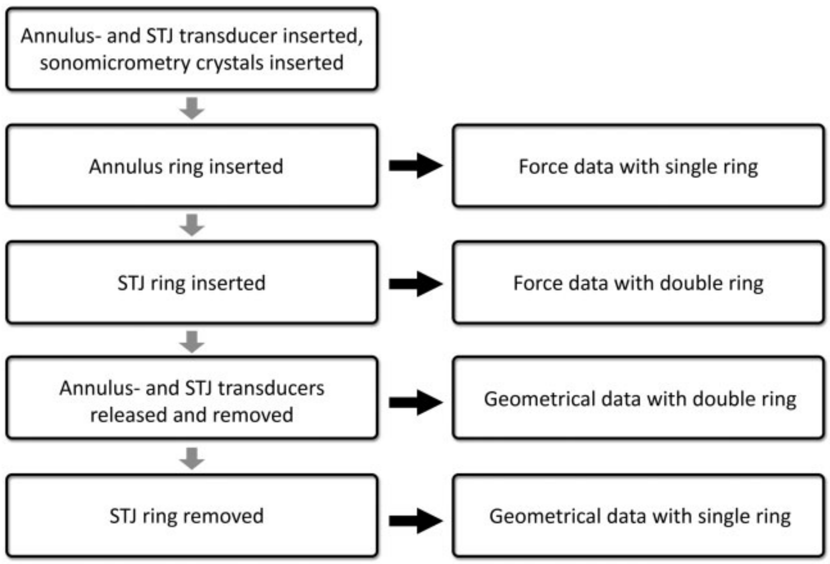


Figure 3: Flowchart of the surgical and experimental protocol with data recordings. STJ: sinotubular junction.

with an overdose of pentobarbital. The heart was excised and the position of the sonomicrometry crystals and annuloplasties were verified. All animals were operated under standardized conditions by the same surgeon.

Data acquisition and data analysis

The time derivative of left ventricular pressure (LV dP/dt) was used for synchronization between the analogue and sonomicrometry signals. The time points were defined as follows:

- Mid-systole (MS): time point between LV dP/dt maximum and minimum.
- Mid-diastole (MD): time point between LV dP/dt minimum and maximum.
- Minimum (Min) and maximum (Max): amplitude minimum and maximum with respect to each single parameter reported.

Force measurements were reported from MD to MS (MS–MD). Geometrical values were reported from minimum to maximum (Max–Min). Expansibility was calculated as the change in area from Min to Max divided by the Min area. Three segmental distances corresponding to the segmental force measurements were used for analysis, i.e. the length of the LN, the RN and the LR for both the annular level and the STJ level. For analysis of the shape of the aortic annulus and STJ, 3 anatomical cross-sectional diameters were calculated, that corresponded to the sinus-commissure diameter for each segment throughout the cardiac cycle, i.e. the distance from the non-coronary sinus to LR (NC–LR), right coronary sinus to LN and left coronary sinus to RN (Fig. 2). The difference between the smallest and largest cross-sectional diameter was calculated as a measure of the sphericity and reported at MS and MD. The definition by Tops *et al.* [20] was used, which defined the structure as oval if the difference between 2 cross-sectional diameters was >3 mm.

Statistical analysis

All data are presented as mean ± standard deviation from 10 consecutive heart cycles with a significance level of *P*-value <0.05. The collected data were analysed by two-way repeated-measures analysis of variance (ANOVA) using group and repetitive heart cycles as factors. The model allowed for different residual variations in the

EXPERIMENTAL

Table 1: Haemodynamic parameters in the 2 groups with and without force transducers

Parameter	With force transducers			Without force transducers		
	Single ring	Double ring	*P*-value	Single ring	Double ring	*P*-value
HR (min^{-1})	87 ± 15	101 ± 15	NS	108 ± 18	102 ± 19	NS
LVP max (mmHg)	106 ± 14	110 ± 14	NS	87 ± 11	99 ± 15	NS
TvP max (mmHg)	38 ± 14	43 ± 17	0.04	21 ± 7	33 ± 17	0.04
LV dP/dt max (mmHg/s)	1833 ± 432	1778 ± 416	NS	1589 ± 429	1675 ± 442	NS
Total ECC time (min)			276 ± 36			
Cross-clamp time (min)			149 ± 12			

All data are presented as mean ± standard deviation.

ECC: extracorporeal circulation; HR: heart rate; LVP: left ventricular pressure; Max: maximum; LV dP/dt: time derivative of left ventricular pressure; TvP: transvalvular pressure; NS: non-significant.

groups. Residuals were inspected for normality by QQ-plots and residuals versus fitted values and no reason to refute was found. Groups were then compared using *post hoc* Wald *z*-tests. No corrections were performed for multiple testing. Heart rate was compared between groups using a paired *t*-test. The data were analysed using Stata 13.0 (StataCorp LLC, College Station, TX, USA), and the statistical models were performed with support from Biostatistical Advisory Service, University of Aarhus, Denmark.

RESULTS

Haemodynamic results

Haemodynamic parameters are presented in Table 1. There was no significant difference between ventricular pressure, LV dP/dt or heart rate between groups. There was a significantly higher transvalvular pressure loss within both groups with the force transducers *in situ* corresponding to a mild stenosis. However, there was no significant difference in transvalvular pressure with the force transducers implanted between the 2 groups. The double-ring procedure itself caused a significant increase in transvalvular pressure loss compared with a single ring (double ring: 33 ± 17 mmHg; single ring: 21 ± 7 mmHg, $P = 0.04$). All pigs had no or trivial aortic insufficiency at any time during the procedure.

Force results

Segmental force results for the aortic annulus and STJ from MS–MD are presented in Fig. 4 and summarized in Table 2. The total force acting in the STJ from MS–MD was significantly reduced in the double-ring group compared with the single-ring group from 1.7 ± 0.6 to 0.04 ± 1.1 N ($P = 0.001$). There was no significant difference in the total force at the aortic annulus (single ring: 6.7 ± 3.3 N; double ring: 6.6 ± 2.2 N, $P = 0.94$), nor any difference in the segmental forces in the aortic annulus. In the STJ, there was a reduced force in the RN and LR segments, but not in the LN segment after double ring compared with single ring. There was a significantly higher force in the LR segment compared with the 2 other segments in the aortic annulus within each group. In the STJ, there was no significant difference in force between segments within each group.

Geometrical results

Geometrical results are summarized in Table 3. Area and circumference for the annulus and STJ are presented in Fig. 5A and B. Area and circumference in the double-ring group compared with the single-ring group were significantly reduced at the STJ but not in the annulus. We found significantly reduced expansibility in the STJ with double ring compared with single ring, but no difference in the annulus was observed between the groups.

Both in the aortic annulus and the STJ, there was no significant difference between segment expansion within each group. All 3 segments were reduced with double ring compared with single ring at the STJ, however, only significantly for the RN segment. In the aortic annulus, there was no difference between the length and expansion of the segments between the 2 groups.

The cross-sectional diameters in the annulus and STJ are presented at 4 defined time points throughout the cardiac cycle in Fig. 5C and D. At the STJ, the largest cross-sectional diameter was the NC–LR segment in both the single- and double-ring groups. The expansion in cross-sectional diameters at the STJ was not statistically different between the 3 segments within each group. In the aortic annulus, the largest cross-sectional diameter was also the NC–LR segment in both groups. However, the expansion was different within both groups with the largest expansion at the right coronary sinus to LN and the smallest expansion at the left coronary sinus to RN. The shape of the aortic annulus was oval and remained unchanged after single ring and double ring [20], and the shape was more circular at MD compared with MS. In the STJ, the shape was primarily circular at both MS and MD in the single-ring group, but became more oval after the double ring. However, the sphericity in the STJ was maintained throughout the cardiac cycle in each group, thus there was no change in shape configuration within each group.

DISCUSSION

From this acute porcine study, we aimed to evaluate the segmental geometrical changes and radial stress distribution in the aortic annulus and STJ after both single-ring annuloplasty and double-ring annuloplasty. This study is the first to systematically and reproducibly compare the single-ring annuloplasty with the double-ring annuloplasty under standardized conditions with detailed geometry and force measurements *in vivo*. The model was successful for the intended characterization with detailed dynamic mapping of stress distribution and geometrical changes in the aortic annulus and STJ throughout the cardiac cycle for the 2 groups.

In the aortic annulus, the highest stresses were found in the LR segment and the lowest stresses in the LN segment. Grande *et al.*

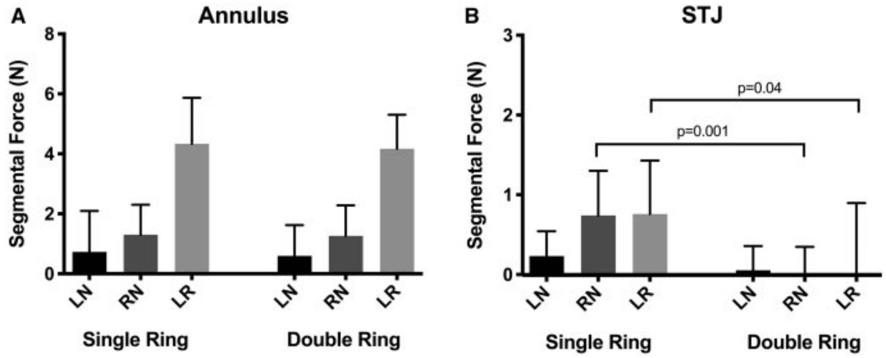


Figure 4: Segmental force for each of the 3 segments (LN, RN, LR) for single and double ring (mid-systole–mid-diastole). (**A**) Level of the annulus. (**B**) Level of the STJ (mean ± standard deviation). LN: left/non-coronary segment; LR: left/right-coronary segment; RN: right/non-coronary segment; STJ: Sinotubular junction.

Table 2: Segmental force at the level of the annulus and STJ from MD to MS for both groups

Force (N)	Single ring	Double ring	*P*-value between groups
Annulus LN segment	0.7 ± 1.4	0.6 ± 1.0	NS
Annulus RN segment	1.3 ± 1.0	1.3 ± 1.0	NS
Annulus LR segment	4.3 ± 1.5	4.2 ± 1.1	NS
STJ LN segment	0.2 ± 0.3	0.1 ± 0.3	NS
STJ RN segment	0.7 ± 0.6	0.0 ± 0.3	0.001
STJ LR segment	0.8 ± 0.7	0.0 ± 0.9	0.041

All data are presented as mean ± standard deviation.

LN: left/non-coronary segment; LR: left/right-coronary segment; MD: mid-diastole; MS: mid-systole; NS: non-significant; RN: right/non-coronary segment; STJ: Sinotubular junction.

[21] investigated 9 human homografts and the stress variations occurring in the aortic root with a finite element model. They found the highest stresses in the right coronary sinus and NC, and the lowest stresses in the left sinus. The authors concluded that the low stresses at the NC might be due to an absent coronary ostium, which relieves the blood pressure loading in the aortic root. The radial stresses in the current study, were, however, measured upstream of the aortic valve, thus the pressure relief of a coronary ostium would not apply to these measurements. The heterogenicity in the measured stresses is most likely caused by differences in tissue composition. The aortic annulus consists of not only muscular tissue as part of the interventricular septum but also fibrous tissue as part of the anterior leaflet of the mitral valve. We have previously found that the native aortic annulus is heterogeneous in both force distribution and dynamics throughout the cardiac cycle, which confirms the results in this study [14].

An additional ring in the STJ did not change the force distribution in the aortic annulus; however, it reduced the forces at all 3 segments in the STJ. The STJ is much more homogenous in tissue composition, and consists primarily of elastic tissue with a high content of elastin and collagen in all 3 segments, which intuitively provides a more even stress distribution in the 3 segments of the STJ. The radial stress distribution in the STJ was almost reduced to zero after an additional ring in the STJ, which is desirable when performing aortic valve repair to minimize the risk of post-operative redilatation.

The expansibility of the STJ was reduced in the double-ring group compared with the single-ring group. In contrast, our group has previously shown that expansibility in the aortic annulus is preserved after implantation of a subvalvular annuloplasty ring of 11% [15], which is within the normal range of aortic annulus expansion [6, 11]. The reduced expansibility with an annuloplasty ring at the STJ compared with the aortic annulus could be that the deformational capacity of the Dacron ring is exceeded by the hyperdynamic aortic tissue at the STJ.

Lansac *et al.* [3] investigated the double-ring procedure in patients with isolated aortic insufficiency and a dilated aortic annulus >25 mm. They found a slight reduction of recurrent aortic insufficiency grade ≥2 and ≥3 after the double-ring procedure compared with a single subvalvular ring at 4-year follow-up, which indicates an instability of the aortic root with only one subvalvular annuloplasty ring. Redilatation of the STJ over time is a known risk factor for recurrent aortic insufficiency after aortic valve-sparing procedures [4]. A plausible explanation could be that the STJ-annulus ratio is distorted when only the aortic annulus and not the STJ is stabilized. Persistent radial stress in the STJ could thus be a culprit for later redilatation of the aortic root. Maselli *et al.* [22] investigated the optimal STJ-annulus ratio on porcine aortic roots, and found that the optimal STJ-annulus ratio is 1.0. Marom *et al.* [23] investigated the optimal STJ-annulus ratio in a numerical model, and found that the optimal ratio with lowest stresses is 0.8–1.0 with an aortic annulus diameter of 22 mm. Finally, Lansac *et al.* [16] also investigated the STJ-annulus ratio in sheep with sonomicrometry, and they found that the ratio was 0.69–0.73. Several studies confirm that the geometrical relationship between the aortic annulus and STJ is a key factor for a successful aortic valve-sparing procedure. Implanting an additional ring at the STJ could therefore potentially ensure that this relationship remains constant over time [3, 6].

The optimal material for an annuloplasty ring is still uncertain. The optimal material of a supravalvular annuloplasty should be able to downsize effectively, while preserving normal physiological expansion of the STJ of approximately 15–20% throughout the cardiac cycle. Choice of material and future improvements of dedicated material for the annuloplasty procedures remain a challenge for future studies. These results underline the importance of addressing and stabilizing the functional aortic annulus when performing aortic valve repair. We propose that the double annuloplasty procedure should be used in patients with isolated aortic insufficiency and a dilated aortic annulus to stabilize the entire functional aortic annulus.

Table 3: Area, circumference, segmental distance and cross-sectional diameters at the annulus and STJ for both groups

Parameter	Single ring			Double ring			*P*-value between groups		
	Max	Min	Change %	Max	Min	Change %	Max	Min	Change %
Annulus area (mm^2)	320.9 ± 40.5	286.2 ± 33.5	12.1 ± 3.8	321.3 ± 38.8	282.8 ± 34.7	13.7 ± 5.5	NS	NS	NS
Annulus circumference (mm)	70.8 ± 3.8	67.2 ± 3.5	5.4 ± 1.1	71.6 ± 3.9	67.6 ± 3.5	6.0 ± 2.0	NS	NS	NS
STJ area (mm^2)	234.8 ± 37.6	201.8 ± 36.5	16.9 ± 6.4	147.5 ± 31.8	136.6 ± 30.7	8.2 ± 3.1	<0.001	<0.001	0.001
STJ circumference (mm)	60.4 ± 4.9	56.5 ± 5.2	7.0 ± 3.1	49.3 ± 5.5	47.5 ± 5.5	4.1 ± 1.8	<0.001	<0.001	0.02
Annulus left/non-segment (mm)	22.1 ± 2.2	20.6 ± 1.9	6.9 ± 2.8	22.1 ± 2.5	20.5 ± 1.9	7.7 ± 3.2	NS	NS	NS
Annulus right/non-segment (mm)	20.1 ± 2.3	18.7 ± 1.9	7.6 ± 1.6	21.2 ± 3.7	19.6 ± 3.4	8.2 ± 3.6	NS	NS	NS
Annulus left/right segment (mm)	28.9 ± 3.9	27.4 ± 3.7	5.5 ± 2.0	28.6 ± 4.0	26.9 ± 4.0	6.5 ± 2.4	NS	NS	NS
STJ left/non-segment (mm)	19.4 ± 2.4	18.3 ± 2.3	6.4 ± 3.6	17.1 ± 2.3	16.4 ± 2.3	4.7 ± 1.4	NS	NS	NS
STJ right/non-segment (mm)	19.6 ± 2.9	18.1 ± 3.0	8.2 ± 3.4	15.1 ± 3.5	14.4 ± 3.4	4.8 ± 1.8	0.005	0.02	0.01
STJ left/right segment (mm)	21.4 ± 2.0	19.9 ± 1.8	7.4 ± 3.9	17.1 ± 2.2	16.3 ± 2.0	4.9 ± 3.0	<0.001	<0.001	NS
Annulus crystal NC–LR (crystal 1–4)	25.8 ± 1.5	23.3 ± 1.4	10.4 ± 3.2	25.6 ± 1.6	23.1 ± 1.4	11.0 ± 3.5	NS	NS	NS
Annulus crystal RC–LN (crystal 2–5)	18.8 ± 2.9	16.4 ± 2.4	14.6 ± 3.6	19.3 ± 3.0	16.8 ± 2.6	14.8 ± 4.0	NS	NS	NS
Annulus crystal LC–RN (crystal 3–6)	22.7 ± 2.2	21.5 ± 2.3	5.8 ± 2.8	22.0 ± 1.9	20.3 ± 1.7	8.0 ± 3.1	NS	NS	NS
STJ crystal NC–LR (crystal 7–10)	20.3 ± 1.8	18.7 ± 1.6	8.6 ± 3.5	15.8 ± 1.7	15.2 ± 1.7	4.1 ± 1.9	<0.001	<0.001	0.001
STJ crystal RC–LN (crystal 8–11)	17.8 ± 1.3	16.4 ± 1.2	8.8 ± 3.6	13.5 ± 2.3	12.9 ± 2.3	5.1 ± 2.5	<0.001	<0.001	0.009
STJ crystal LC–RN (crystal 9–12)	18.7 ± 2.1	17.6 ± 2.1	6.6 ± 3.9	15.4 ± 1.6	14.6 ± 1.8	5.7 ± 2.4	<0.001	0.001	NS

All data are presented as mean ± standard deviation. Crystals 1–12 representing sonomicrometry crystals.

LC: left coronary sinus; LN: left/non-coronary segment; LR: left/right-coronary segment; Max: maximum; Min: minimum; NC: non-coronary sinus; NS: non-significant; RC: right coronary sinus; RN: right/non-coronary segment; STJ: sinotubular junction.

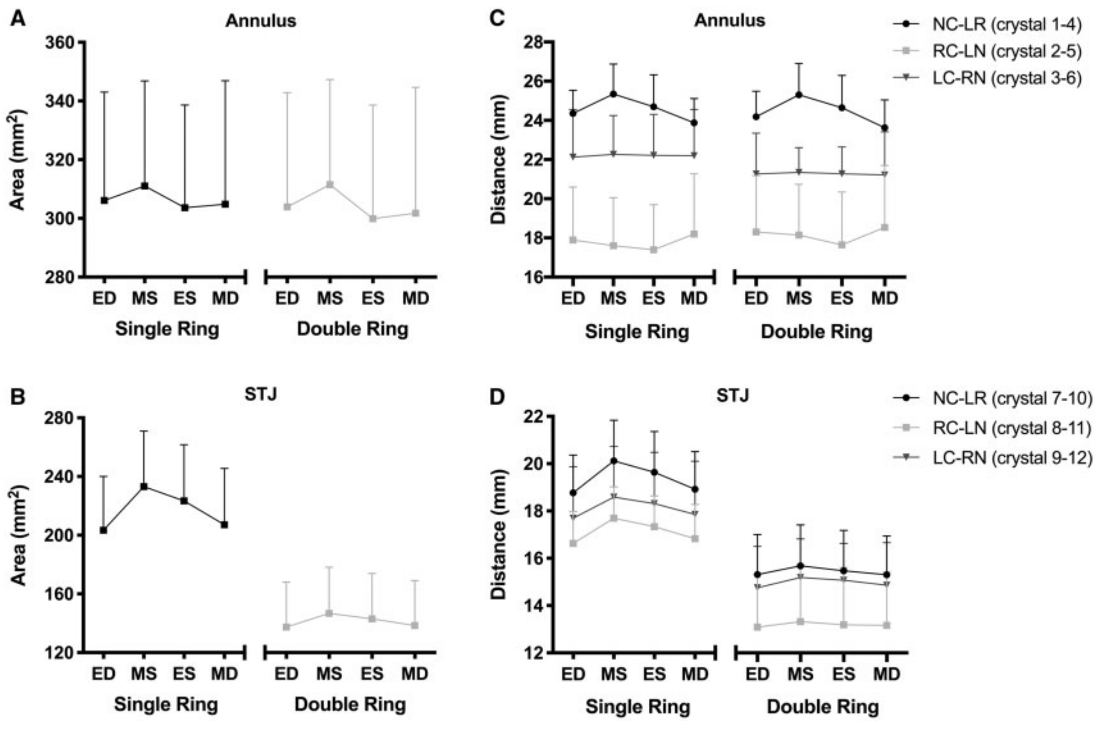


Figure 5: (**A** and **B**) Area at 4 defined time points (ED, MS, ES, MD) throughout the cardiac cycle for single and double rings at the annulus and STJ. (**C** and **D**) Cross-sectional diameters NC–LR, RC–LN and LC–RN at 4 defined time points throughout the cardiac cycle for single and double rings at the annulus and STJ (mean ± standard deviation). ED: end-diastole; ES: end-systole; LC: left coronary sinus; LN: left/non-coronary segment; LR: left/right-coronary segment; MD: mid-diastole; MS: mid-systole; NC: non-coronary sinus; RC: right coronary sinus; RN: right/non-coronary segment; STJ: sinotubular junction.

Limitations

Porcine hearts have a wide septal muscle shelf near the right cusp, which could change the geometry in the aortic annulus. However, the porcine model is an acknowledged and widely used model with low interindividual variation, which facilitates assessment of surgical procedures. Due to the close proximity of the left coronary artery to the myocardium in pigs, the Dacron ring was not closed. The difference observed between the 2 interventions could be caused by ventricular fatigue; however, there was no observed difference in LV dP/dt between the 2 groups, which is a measure of ventricular performance. Our animal model is a healthy acute model, which defrays conclusions on the long-term effects of an annuloplasty ring in patients. Nonetheless, the effect of the annuloplasty on stress distribution and geometry is new insight and should be confirmed in long-term studies. In pigs, the aortic annulus is larger than the STJ; however, in humans the STJ is larger than the aortic annulus [24, 25]. This would result in a larger STJ ring compared with the ring at the aortic annulus, and therefore a different STJ/annulus ratio would apply for humans.

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Author contributions

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