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Acute Effect of Mitral Valve Repair on Mitral Valve Geometry

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Abstract

Background The aim of this study was to quantify acute mitral valve (MV) geometry dynamic changes throughout the cardiac cycle using three-dimensional transesophageal echocardiography (3D TEE) in patients undergoing surgical MV repair (MVR) with ring annuloplasty and optional neochord implantation.

Methods Twenty-nine patients (63 ± 10 years) with severe primary mitral regurgitation underwent surgical MVR using ring annuloplasty with or without neochord implantation. We recorded 3D TEE data throughout the cardiac cycle before and after MVR. Dynamic changes (4D) in the MV annulus geometry and anatomical MV orifice area (AMVOA) were measured using a novel semiautomated software (Auto Valve, Siemens Healthcare).

Results MVR significantly reduces the anteroposterior diameter by up to 38% at end-systole (36.8–22.7 mm; $p < 0.001$) and the lateromedial diameter by up to 31% (42.7–30.3 mm; $p < 0.001$). Moreover, the annular circumference was reduced by up to 31% at end-systole (129.6–87.6 mm, $p < 0.001$), and the annular area was significantly decreased by up to 52% (12.8–5.7 cm^2; $p < 0.001$). Finally, the AMVOA experienced the largest change, decreasing from 1.1 to 0.2 cm^2 during systole (at midsystole; $p < 0.001$) and from 4.1 to 3.2 cm^2 ($p < 0.001$) during diastole.

Conclusions MVR reduces the annular dimension and the AMVOA, contributing to mitral competency, but the use of annuloplasty rings reduces annular contractility after the procedure. Surgeons can use 4D imaging technology to assess MV function dynamically, detecting the acute morphological changes of the mitral annulus and leaflets before and after the procedure.

Keywords
- mitral valve repair
- mitral regurgitation
- mitral valve model
- 3D echocardiography
- mitral valve geometry

Introduction

The mitral valve repair (MVR) with ring annuloplasty and optional leaflet resection or neochordal replacement are the preferred surgical techniques for the treatment of severe primary mitral regurgitation (MR).[1,2] Ring annuloplasty results in an annular dimension reduction that optimizes annular function and leaflet stress distribution.[3,4] But, the influence of the technique on MV dynamics in patients with primary MR has not been well described.

The mitral valve (MV) is a geometrically complex and mobile structure, and the annulus and leaflet geometries vary throughout the cardiac cycle.[5] The introduction of three-dimensional transesophageal echocardiography (3D TEE)

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with computational MV models, allowing for the quantification of morphological MV changes, has allowed for an improved understanding of MV dynamics.[6–10] However, a newly developed four-dimensional (4D) MV model, based on 3D TEE data, allows for the comprehensive quantification of MV annulus and morphological changes of leaflets throughout the cardiac cycle.[11] Preliminary studies have suggested that the 4D quantification of MV changes throughout the cardiac cycle is feasible, reproducible, and reliable.[11,12]

Thus, the purpose of this study was to investigate the immediate changes in annular dimension, annular shape, and anatomical MV orifice area (AMVOA) throughout the cardiac cycle using the 3D TEE based 4D MV model after surgical repair with ring annuloplasty and optional neochord implantation.

Patients and Methods

Patients

In 2015, we enrolled 36 consecutive patients in a single-center observation study to assess the dynamic changes of MV geometry before and after surgical MVR. Of the 36 patients, 29 had complete pre- and postoperative 3D TEE datasets for offline 4D reconstruction of MV geometry. We could not acquire the complete cardiac cycle data for three patients, the frame rate was $\leq$8 frames per cardiac cycle in two patients, and stitching artifacts hindered successful MV quantification in two patients.

All 29 patients underwent surgical MVR with ring annuloplasty and/or neochord implantation. We included patients with primary MR and MVR indications according to the current guidelines,[1,2] as well as patients with tricuspid regurgitation and/or atrial fibrillation (AFib) with surgical treatment indications. We excluded patients with ischemic MR, MV, and/or tricuspid valve (TV) infectious endocarditis, and general contraindications for intraoperative TEE. The local ethics committee approved the study, which was performed in concordance with the Declaration of Helsinki. All patients provided written inform consents before the intervention.

Surgical Mitral Valve Repair

Surgical procedures were performed by means of conventional full sternotomy or our standard minimally invasive technique (right lateral mini-thoracotomy and femoral cannulation).[13] Surgeons treated the primary MR with ring annuloplasty in all patients and with neochords in loop technique if indicated, and they selected the ring type and size according to each patient's anterior leaflet length, the commissural width, or the intertrigonal (IT) distance.

Echocardiography

Echocardiographic measurements were performed following the recommendations of the American Society of Echocardiography and the European Association of Echocardiography.[14,15] 3D TEE imaging was performed using an iE33 ultrasound system equipped with an X7–2t transesophageal echocardiography matrix transducer (Philips, Andover, Massachusetts, United States). Electrocardiographically gated TEE full-volume and 3D zoom datasets from the MV were acquired under stable hemodynamic conditions with the patient in the supine position (under general anesthesia) before the start of the surgery and after the surgery (before removing the probe). MR and mitral stenosis severity after the procedure were assessed as published.[14–16]

Four-Dimensional Assessment of Mitral Valve

For 4D quantification, we used the Auto Valve advanced analysis software (Siemens Healthcare, Mountain View, California, United States) as published.[11,12] This semiautomated software tool allows for optional manual adjustments. The workflow and MV model are presented in ►**Fig. 1**. All selected 3D TEE datasets were screened for suitability for 4D quantification. We excluded sets with frame rates $\leq$ 8 frames per cardiac cycle, sets lacking comprehensive MV acquisition throughout the cardiac cycle, and sets with stitching artifacts

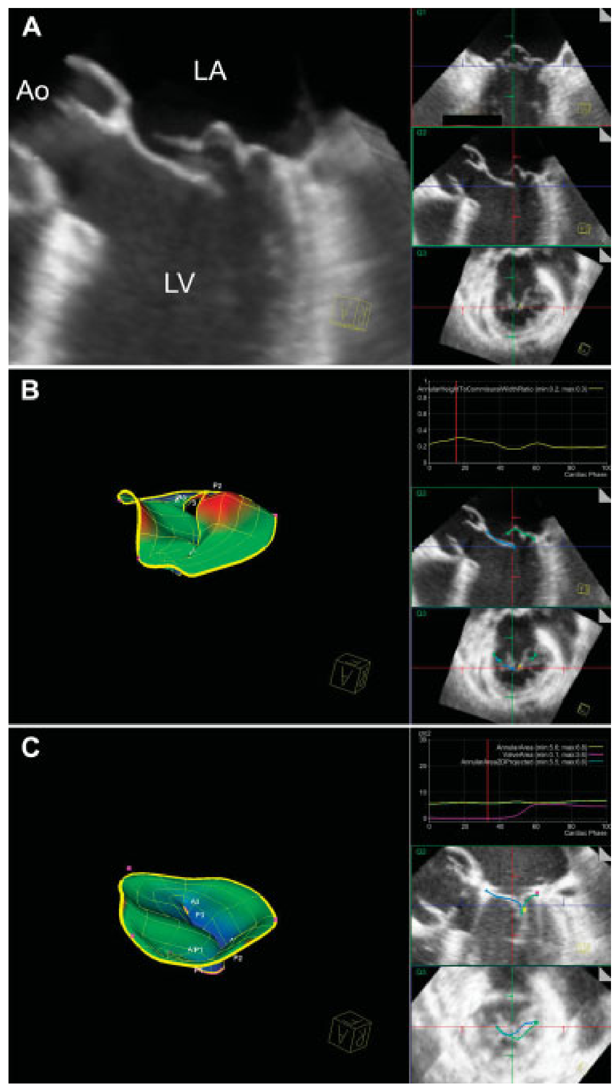

Fig. 1 Mitral valve (MV) assessment using a four-dimensional quantification software. (**A**) Three-dimensional transesophageal echocardiography image in midsystole shows severe P2 prolapse. (**B**) Assessment of MV morphology in midsystole by the MV model before surgical MV repair. (**C**) Assessment of MV in midsystole after surgical MV repair. LA, left atrium; LV, left ventricle; Ao, ascending aorta.

hindering quantification. The datasets had an average of 20.1 frames per cardiac cycle before MVR and 14.5 frames per cardiac cycle after MVR. We defined the beginning of systole as the exact frame before aortic valve opening, and the end of diastole as the exact frame showing complete MV closure. Relevant MV variables such as the AMVOA, anteroposterior diameter (AP diameter), LM diameter, IT distance, annular circumference, annular area, annular sphericity index, and annular height to commissural width ratio (AHCWR) were measured throughout the cardiac cycle. The computed AHCWR describes the annular saddle shape. The higher the grade of AHCWR, the higher the extent of the saddle shape.

The AMVOA was defined as the MV orifice projected into its least-square plane and was computed over the completed cardiac cycle. The annular sphericity index refers to the ratio between the AP and the LM diameters. We exported the measured data for statistical analysis per percentage of the cardiac cycle (from 0 to 100% in steps of 10%). MV measurements were taken six times during the cardiac cycle in early systole (10% of cardiac cycle), midsystole (20% of cardiac cycle), and end-systole (30% of cardiac cycle) and in early diastole (40% of cardiac cycle), middiastole (70% of cardiac cycle), and end-diastole (100% of cardiac cycle). ►**Fig. 2** shows a representation of the quantification of the MV geometry throughout the cardiac cycle with the six specific time points during the cardiac cycle. All measurements were decided by consensus between two readers (T. N. and K. W.) unaware of the clinical history and the outcome of surgical MVR.

Statistical Analysis

We tested the data for normality using the D'Agostino and Pearson omnibus normality test. Normally distributed data are expressed as mean $\pm$ standard deviation, and categorical data as proportions and percentages. We used a paired *t*-test to evaluate for statistically significant differences between measurements. Values of $p < 0.05$ were considered statistically significant. Analyses were performed using the IBM SPSS Statistics Version 20 (SPSS, Chicago, Illinois, United States) software for Mac OS X (Apple).

Results

Patient Population

Patient characteristics are presented in ►**Table 1**. All patients presented chronic primary MR. During the intraoperative TEE, the MR was graded severe in 3 patients and moderate to severe in 26 patients. Two patients were diagnosed as having Barlow's disease.

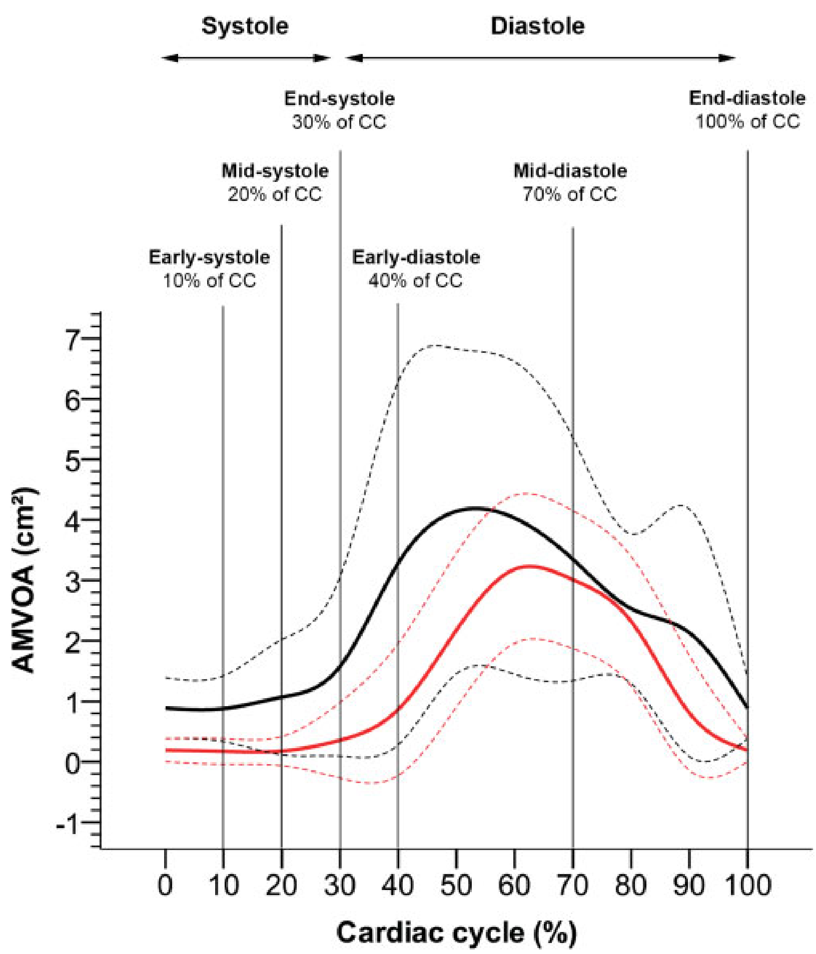

Fig. 2 Representation of the quantification of the mitral valve geometry throughout the cardiac cycle, and the definition of six specific times during the cardiac cycle (early systole, midsystole, end-systole, early diastole, middiastole, and end-diastole) using examples from the anatomical mitral valve orifice area (AMVOA).

Table 1 Baseline patient characteristics

Variable	All patients ($n = 29$)
Age, years	63 ± 10
Men	19 (66%)
BMI, kg/m^2	25 ± 3
MR severity grade	
3+ (moderate to severe)	26 (90%)
4+ (severe)	3 (10%)
Chronic primary MR	29 (100%)
Carpentier functional class	
II	29 (100%)
Vena contracta, mm	7 ± 2
TR severity grade	
1+ (mild)	11 (38%)
2+ (moderate)	4 (14%)
3+ (moderate to severe)	2 (7%)
LVEF, %	62 ± 11

Abbreviations: BMI, body mass index; LVEF, left ventricular ejection fraction; MR, mitral regurgitation; TR, tricuspid regurgitation.

Table 2 Distribution of implanted annuloplasty rings and sizes

Variable	All patients ($n = 29$)
Carpentier–Edwards Physio ring	
28 mm	2 (7%)
30 mm	6 (21%)
32 mm	4 (14%)
34 mm	6 (21%)
36 mm	2 (7%)
38 mm	1 (3%)
40 mm	3 (10%)
Carpentier–Edwards Physio II ring	
30 mm	1 (3%)
34 mm	1 (3%)
40 mm	1 (3%)
SJM Rigid Saddle Ring	
34 mm	1 (3%)
Carpentier–McCarthy–Adams IMR ETlogix ring	
34 mm	1 (3%)

Surgical Procedures

All patients underwent successful MVRs with annuloplasty ring implantation. Surgeons used different annuloplasty ring types: 24 CE Physio (Edwards Lifesciences, Irvine, California, United States) 3 CE Physio II (Edwards Lifesciences), 1 SJM Rigid Saddle Ring (St. Jude Medical, Plymouth, Minnesota), and 1 IMR ETlogix Ring (Edwards Lifesciences). ►**Table 2** presents the distribution of implanted annuloplasty rings and sizes. Six (21%) patients underwent concomitant TV repair with a Cosgrove Band (Edwards Lifesciences). Other concomitant procedures included closure of atrial septum defects in 8 patients (28%), ablations for AFib in 13 patients (45%), and ascending aorta replacement in 1 patient (3%). The mean cardiopulmonary bypass time was 133 ± 37 minutes and the mean cross-clamp time was 82 ± 27 minutes. There was one inhospital death due to postoperative multiorgan failure.

Anatomical Mitral Valve Orifice Area

We found that surgical MVR reduced the AMVOA throughout the cardiac cycle. During systole, the AMVOA (comparable to the anatomical MV regurgitant orifice area, AROA) decreased by 0.7 to 1.2 cm^2 (−77.8 to −81.8%; $p < 0.001$; ►**Fig. 3A**). In addition, the AMVOA was reduced during diastole by 0.3 to 1.9 cm^2 (−8 to −46.3%; p-range: <0.001–0.435). The maximum AMVOA was reduced from 4.1 cm^2 at 50% of the cardiac cycle to 3.2 cm^2 at 60% of the cardiac cycle. During middiastole, the AMVOA was not significantly reduced after surgical MVR. Detailed numbers of AMVOA are given in ►**Table 3** and ►**Supplementary Table 1** (available online only).

Annular Dimensions

Surgical MVR with ring annuloplasty significantly reduced the AP diameter in all cardiac phases by 11.3 to 14.1 mm (−33.4 to −38.3%; $p < 0.001$) with a maximum decrease at end-systole (36.8 vs. 22.7 mm; $p < 0.001$; ►**Fig. 3C**). The LM diameter was also decreased throughout the cardiac cycle by 11 to 12.9 mm (−26.1 to −30.1%; $p < 0.001$). The maximum LM diameter decrease was identified at 0/100% of the cardiac cycle (43.2 vs. 30.2 mm; $p < 0.001$; ►**Fig. 3D**).

The IT distance was decreased in all cardiac phases by 5.5 to 6.7 mm (−19.6 to −22.9%; $p < 0.001$; ►**Fig. 3B**) with a maximal reduction at 80% of the cardiac cycle (29.2 vs. 22.5 mm; $p < 0.001$).

The annular circumference was reduced significantly by 36.3 to 43.6 mm (−31 to −33.3%; $p <0.001$) with a maximum reduction at 20% of the cardiac cycle (130.8 vs. 87.2 mm; $p < 0.001$; ►**Fig. 3E**). Moreover, the annular area was reduced in all cardiac phases by 6 to 7.3 cm^2 (−49.2 to −56.6%; $p < 0.001$) with a maximal reduction during midsystole (12.9 vs. 5.6 cm^2; $p < 0.001$; ►**Fig. 3D**).

The preoperative annular dynamic with an increased AP diameter during systole was terminated and not further detected after surgical MVR.

Detailed numbers of annular dimensions are given in ►**Table 3** and ►**Supplementary Tables 1** and **2** (available online only).

Annular Shape

The reduced AP and LM diameters resulted in a significant reduction of the annular sphericity index by 0.08 to 0.15 (−9.6 to −16.5%; $p < 0.001$) throughout the cardiac cycle (►**Fig. 3G**). The maximum reduction was identified at the end-systolic and early diastolic phases (0.91 vs. 0.76; $p < 0.001$).

Surgical MVR led to a decrease in the AHCWR throughout the cardiac cycle by 0.04 to 0.12 (−18.8 to −50%, p-range: <0.001–0.019; ►**Fig. 3H**). We found the maximal reduction

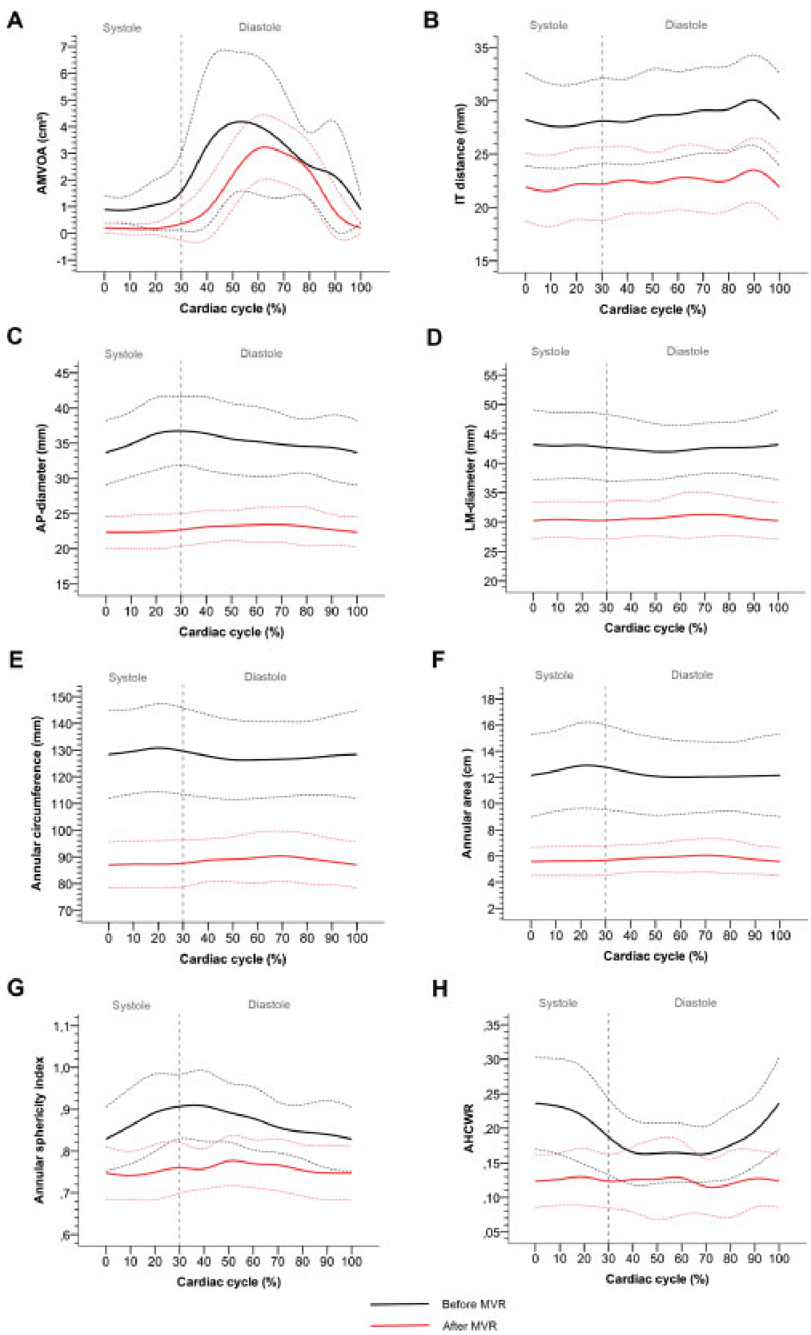

Fig. 3 Mitral valve geometry throughout the cardiac cycle before and after mitral valve (MV) repair. (**A**) Anatomical MV orifice area, (**B**) intertrigonal distance, (**C**) anteroposterior diameter, (**D**) lateromedial diameter, (**E**) annular circumference, (**F**) annular area, (**G**) annular sphericity index, and (**H**) annular height to commissural width ratio. AHCW, annular height to commissural width ratio; AMVOA, anatomical mitral valve orifice area; AP, anteroposterior; IT, intertrigonal; LM, lateromedial; MV, mitral valve; MVR, mitral valve repair.

at 0/100% of the cardiac cycle (0.23 vs. 0.12; $p < 0.001$). Also, the dynamics of the AHCWR before surgery were terminated after the procedure.

Detailed numbers of annular dimensions are given in ►**Table 3** and ►**Supplementary Table 2** (available online only).

Comment

This study identified the acute effects of MVR with ring annuloplasty on the MV geometry in relation to the cardiac cycle. To the best of our knowledge, this is the first study demonstrating dynamic changes of the mitral annulus and leaflets after its repair. Our results underlined the curative effect of ring annuloplasty with or without neochord implantation for primary MR by showing a decrease in all annular measurements and the AMVOA throughout the cardiac cycle. The surgical procedure we used resulted in a natural 3:4 ratio between the AP and LM diameters but gave rise to an undersized mitral annulus compared with that in normal patients in published studies.[8] We were not able to observe

Table 3 MV geometry throughout the cardiac cycle before and after MVR ($n = 29$)

Variable	Early systole (10% of CC)		Midsystole (20% of CC)		End-systole (30% of CC)		Early diastole (40% of CC)		Middiastole (70% of CC)		End-diastole (100% of CC)	
	Before MVR	After MVR	Before MVR	After MVR	Before MVR	After MVR	Before MVR	After MVR	Before MVR	After MVR	Before MVR	After MVR
Anatomical MV orifice area												
AMVOA, cm^2	0.9 ± 0.5	0.2 ± 0.2[a]	1.1 ± 1	0.2 ± 0.2[a]	1.6 ± 1.5[a]	0.4 ± 0.6[a]	3.3 ± 3	0.9 ± 1.1[a]	3.3 ± 2	3 ± 1.1	0.9 ± 0.5	0.2 ± 0.2[a]
Annular dimensions												
AP diameter, mm	34.9 ± 4.6	22.4 ± 2.4[a]	36.4 ± 5.1	22.4 ± 2.4[a]	36.8 ± 4.9	22.7 ± 2.3[a]	36.4 ± 5.2	23.1 ± 2.3[a]	34.8 ± 4.4	23.4 ± 2.5[a]	33.7 ± 4.6	22.4 ± 2.2[a]
LM diameter, mm	43 ± 5.6	30.5 ± 3.1[a]	43.1 ± 5.6	30.4 ± 3.1[a]	42.7 ± 5.6	30.3 ± 3.2[a]	42.3 ± 5.2	30.6 ± 3.1[a]	42.5 ± 4.3	31.3 ± 3.8[a]	43.2 ± 5.9	30.2 ± 3.1[a]
IT distance, mm	27.6 ± 4	21.6 ± 3.3[a]	27.7 ± 3.9	22.2 ± 3.3[a]	28.1 ± 4	22.2 ± 3.4[a]	28 ± 4	22.5 ± 3.2[a]	29.1 ± 4	22.6 ± 3.1[a]	28.2 ± 4.4	21.9 ± 3.2[a]
Annular circumference, mm	129.5 ± 15.9	87.2 ± 8.7[a]	130.8 ± 16.4	87.2 ± 8.9[a]	129.6 ± 16.3	87.6 ± 8.8[a]	127.8 ± 15.4	88.8 ± 8[a]	126.6 ± 14	90.3 ± 9.3[a]	128.4 ± 16.4	87 ± 8.6[a]
Annular area, cm^2	12.5 ± 3.1	5.6 ± 1.1[a]	12.9 ± 3.3	5.6 ± 1.1[a]	12.8 ± 3.2	5.7 ± 1.1[a]	12.4 ± 3.1	5.8 ± 1.1[a]	12 ± 2.7	6.1 ± 1.3[a]	12.2 ± 3.2	5.6 ± 1.1[a]
Annular shape												
Annular sphericity index	0.86 ± 0.09	0.74 ± 0.06[a]	0.89 ± 0.09	0.75 ± 0.07[a]	0.91 ± 0.08	0.76 ± 0.06[a]	0.91 ± 0.08	0.76 ± 0.05[a]	0.86 ± 0.06	0.77 ± 0.06[a]	0.83 ± 0.08	0.75 ± 0.06[a]
AHCWR	0.23 ± 0.07	0.13 ± 0.04[a]	0.22 ± 0.07	0.13 ± 0.04[a]	0.19 ± 0.05	0.12 ± 0.04[a]	0.17 ± 0.05	0.13 ± 0.05[a]	0.16 ± 0.04	0.12 ± 0.04[a]	0.24 ± 0.07	0.12 ± 0.04[a]

Abbreviations: AHCWR, annular height to commissural width ratio; AMVOA, anatomical mitral valve orifice area; AP, anteroposterior; IT, intertrigonal; LM, lateromedial; MV, mitral valve; MVR, mitral valve repair.
[a] $p < 0.05$ before MVR versus after MVR.

the physiologic contractility of the MV annulus during systole with our most frequently implanted semirigid CE Physio annuloplasty ring. And, we believe that the novel 4D imaging techniques used in this study demonstrate new details of the dynamic changes of the MV.

Annular Dimensions and Shape

The increases in annular diameters, circumference, and area cause an annular distortion in patients with MR.[7–10,17–19] Our methodology quantifies the annular variables throughout the cardiac cycle and demonstrates the dynamic changes of the MV annulus (►**Fig. 2**). It is important to note that the AP diameter, annular circumference, and area display late-diastolic contraction and systolic progressive enlargement before MVR. Late-diastolic AP contraction leads to an annular contraction area that approximates the anterior and posterior leaflets.[8,20] This mechanism is important to prevent regurgitation, when the early systolic ventricular pressure is relatively low and leaflet closure has not yet occurred.[8,21] Late-systolic annular enlargement is related to an increased annular traction induced by systolic myocardial contraction and longitudinal ventricular shortening.[8,22] Using 3D echocardiography, Apor et al found evidence for this systolic phenomenon by quantifying a relative increase in the AP diameter of 6% in 27 patients with Barlow disease and of 8% in 32 patients with fibroelastic deficiency.[19] For comparison, in normal subjects without MR, the early systolic contraction leads to AP diameter changes of more than 10%.[8] This supports the idea that the annular distortion and the resulting annular rigidity contribute to the genesis of MR. After the systole, the annular dimensions get decreased by the intraventricular pressure reduction during diastole.

The primary goal of annuloplasty is to restore annular geometry[9] and to improve the coaptation of the MV leaflets by reducing the AP diameter. In our study, we used the closed semirigid Carpentier-Edwards Physio annuloplasty ring most frequently ($n = 24$, 85%). We found that our implanted annuloplasty rings led to significant reductions in annular diameters and circumferences and thus contributed to MR reduction. The normal systolic AP diameter varies between 28 and 32 mm;[7–9] thus, our findings show an abnormally reduced size of the mitral annulus (22.4 mm at 20% of the cardiac cycle), a finding similar to that by Caiani et al who measured a mean AP diameter of 22.1 mm 3 months after surgery.[17] Thus, the implanted rings fix the annulus in a nonphysiological position regarding the mitral annular dimensions of the normal population. This suggests that the ring implantation with the undersized mitral annulus leads to increased radial stress in the annuloplasty ring, preventing systolic annular mobility of the semirigid annuloplasty rings after repair. We did not observe any annular movement after repair in all patients.

Our evidence for dynamic changes of the annular shape includes the annular sphericity index and the AHCWR. Annular sphericity increases with annular dilatation to a more circular-shaped annulus compared with that in a nondilated ellipsoid annulus.[23,24] We found the mean annular sphericity index to be decreased to 0.77 after MVR, which correlates with the 3:4 ratio of our most frequently implanted CE Physio annuloplasty ring (annular sphericity index of 0.75). Moreover, the end-systolic AHCWR also decreased from 0.19 to 0.12, showing no significant changes throughout the cardiac cycle after MVR. The end-systolic AHCWR in normal subjects is 0.21, and it decreases with the presence of severe MR to 0.13.[7] The postoperative AHCWR is primarily influenced by the AHCWR of the implanted annuloplasty ring. Ryan et al found a decrease of AHCWR from 0.19 to 0.11 after implantation of a CE Physio ring with a size of 30 mm.[25] AHCWRs with a preoperative end-systolic value of $\leq$0.15 have been identified as possible predictors for recurrent MR and reoperation.[10] In our study, the mean preoperative end-systolic AHCWR was 0.19. Based on our long-time experience with the CE Physio ring, we did not observe higher incidences of repair failure or reoperation rates than other institutions.[13,26,27]

The selection of the right type of annuloplasty ring depends on many variables and the experience of surgeons in the implanting center. We prefer a semirigid CE Physio annuloplasty ring due to the possibility of restoring the mitral annulus to a natural ratio to allow systolic annular movement.

Anatomical Mitral Valve Orifice Area

Surgical MVR with ring annuloplasty should restore the mitral annulus geometry as well as leaflet mobility to create a large coaptation.[28] In this study, we observed a reduction of the anatomical regurgitation area of 82%, demonstrating the curative effect of the procedure. The postoperative quantification of the anatomical regurgitation area is crucial and depends on the spatial and temporal resolution of 3D TEE data, particularly with very small sizes.[12] Otherwise, we found the presence of a mild residual MR in 23% of the patients correlating with the results of the 4D imaging techniques.

The AMVOA was decreased by 22%. Patients with MR show an increase in the AMVOA due to annular enlargement. In this context, the reduction of the AMVOA after the repair can be interpreted as a result of the reduction of the annular dimension caused by the annuloplasty. Moreover, the undersized mitral annulus after the repair led to a smaller AMVOA compared with the normal AMVOAs. The significant AMVOA reduction could also explain the increase in pressure gradients after MVR.

Limitations

The small number of patients in this study limits its clinical applicability. However, given the novelty of the complex 4D MV assessment, we believe that the sample size is reasonable to reach meaningful conclusions.

In addition, we did not investigate the influence of arrhythmia on the time-adjusted measurements, and future studies are needed to address this.

Finally, in this study, the maximal AMVOA is a time-dependent measure dependent on the length of the cardiac cycle. The time-dependent maximal AMVOA underestimates the true maximal MV orifice area during the MV opening due to the divergent times of MV opening between patients. We confirmed this effect by showing an increase in the standard deviation and the difference between the minimal and maximal AMVOA during this phase of the cardiac cycle (►**Supplementary Table 1**, available online only). The AROA did not change between the time-independent and time-dependent analyses.

Conclusions

The new 3D TEE based 4D analysis for the mitral annulus and the AMVOA shows that the MV is a complex dynamic structure that undergoes geometrical changes throughout the cardiac cycle. MVR using ring annuloplasty with or without neochord implantation leads to a reduction of the pathological annular dilatation and a reduction of the AMVOA. The annular sphericity index after ring implantation shows a physiological relationship between the AP and LM diameters. However, the ring annuloplasty leads to a stiffening of the mitral annulus with loss of late-diastolic annular contraction. Thus, our MV dynamics investigation with the novel 4D imaging technology allowed us to gather new insights into the physiopathological mechanisms of MR and repair.

Authors Contribution

Authorship	Tasks
Noack, T.	Study design Data collection Statistics Manuscript preparation
Wittgen, K.	Data collection Statistics
Kiefer, P.	Data collection Manuscript review Manuscript preparation
Emrich, F.	Data collection Manuscript review
Raschpichler, M.	Manuscript review
Eibel, M.	Data collection Performed intraoperative 3D TEE
Holzhey, D. M.	Performed MV repair (surgeon)
Misfeld, M.	Performed MV repair (surgeon)
Mohr, F. W.	Performed MV repair (surgeon)
Borger, M. A.	Performed MV repair (surgeon) Manuscript preparation
Ender, J.	Performed intraoperative 3D TEE Manuscript review
Seeburger, J.	Study design Manuscript preparation Performed MV repair (surgeon)

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