Does greater post-surgical mitral valve leaflet coaptation area imply better repair durability?

**Image-based reconstruction of full coaptation zone**

- r-3DE Data Series
  - n = 7 nonrecurrent MR
  - n = 7 recurrent MR

  - End-Diastole
  - End-Systole

  - Segmentation and processing

  - Open state mesh
  - Closed state mesh

  - Shape-Matching Method

  - Recovery of full systolic coaptation zone

**Post-repair coaptation area increases more in recurrent patients**

- Coaptation Zone Area
- Normalized Coaptation Area

- Pre-Surgical
- Post-Surgical

- Nonrecurrent
- Recurrent

**Surgical Implications**

- Coaptation area alone may not be a reliable target for repair durability
- In some patients, adverse LV remodeling, aggravated leaflet tethering, and/or advanced leaflet plasticity may play a larger role in the MR disease process
- MV-focused repair may not lead to optimal outcomes in this patient subgroup
- Patient-specific and LV/MV integrated models are crucial for improved treatment planning

**Abbreviations**

- r-3DE: real-time three-dimensional echocardiography
- MR: mitral regurgitation
- LV: left ventricle
Quantitative In-Vivo Assessment of Human Mitral Valve Coaptation Area After Undersized Ring Annuloplasty Repair for Ischemic Mitral Regurgitation

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IRB Approval and Informed Consent: Patient images taken from an extant database of images from Narang et al. and Bouma et al.¹ ²

Total Word Count: 3414
GLOSSARY OF ABBREVIATIONS

MR: mitral regurgitation
IMR: ischemic mitral regurgitation
URA: undersized ring annuloplasty
MV: mitral valve
MI: myocardial infarction
LV: left ventricle
Rt-3DE: real-time three-dimensional echocardiography
FE: finite element
ED: end-diastolic
ES: end-systolic
LCPF: local corrective pressure field
LVEDV: left-ventricular end-diastolic volume
LVESV: left-ventricular end-systolic volume
The coaptation zone is larger in recurrent patients after undersized ring annuloplasty.

CENTRAL MESSAGE (164 char)
Increased mitral valve leaflet coaptation area alone may not be a reliable target for long-term durability in mitral valve repair of ischemic mitral regurgitation.

PERSPECTIVE STATEMENT (394 char)
Patient outcomes of regurgitant mitral valve repair remain unpredictable, due to an incomplete understanding of repair complexities and limitations of echocardiographic imaging. Here, we applied an image-based simulation technique to quantify the coaptation zone in repaired mitral valves and demonstrated that increased coaptation may not be a reliable target for long-term repair durability.
STRUCTURED ABSTRACT (250 words)

**Objectives:** Long-term outcomes of mitral valve repair procedures to correct ischemic mitral regurgitation remain unpredictable, due to an incomplete understanding of the disease process and the inability to reliably quantify the coaptation zone using echocardiography. Our objective was to quantify patient-specific mitral valve coaptation behavior from clinical echocardiographic images obtained pre- and post-repair to assess coaptation restoration and its relationship with long-term repair durability.

**Methods:** To circumvent the limitations of clinical imaging we applied a simulation-based shape-matching technique that allowed high fidelity reconstructions of the complete mitral valve in the systolic configuration. We then applied this method to an extant database of human regurgitant mitral valves pre- and post-undersized ring annuloplasty to quantify the effect of the repair on mitral valve coaptation geometry.

**Results:** Our method was able to successfully resolve the coaptation zone into distinct contacting and redundant regions. Results indicated that in patients whose regurgitation recurred six months post-repair, both the contacting and redundant regions were larger immediately post-repair compared to that of patients with no recurrence (p<0.05), even when normalized to account for generally larger recurrent valves.

**Conclusions:** While increasing leaflet coaptation area is an intuitively obvious way to improve long-term repair durability, this study has implied that this may not be a reliable target for mitral valve repair. This study underscores the importance of a rigorous understanding of the consequences of repair techniques on mitral valve behavior, as well as a patient-specific approach to ischemic mitral regurgitation treatment within the context of mitral valve and left ventricle function.
KEYWORDS

Mitral valve regurgitation, mitral valve repair, mitral valve imaging, mitral valve mechanics, myocardial infarction
INTRODUCTION

Undersized ring annuloplasty is currently the gold standard for mitral valve (MV) repair in ischemic mitral regurgitation (IMR). However, six months after URA repair, up to 30% of IMR patients experience recurrent regurgitation, and long-term outcomes remain unpredictable, suboptimal, and poorly understood. Thus, there is an urgent need for a deeper, quantitative understanding of the functional consequences of MV repair to develop more durable MR treatments.

Given that poor coaptation is the underlying mechanistic driver of MR, restoring normal coaptation would seem to be a critical objective in MV repair. Intuitively it would seem that larger coaptation area signifies better closure and therefore a more durable repair, a syllogism which constitutes one of Carpentier’s three guiding principles of reconstructive MV surgery. However, intraoperative assessment of coaptation pre- or post-repair is inhibited by the poor spatial resolution of real-time three-dimensional echocardiographic (rt-3DE) imaging. Furthermore, in the limited area that is visible, it is currently not possible to distinguish the two leaflets or to resolve any further detail. Consequently, existing methods to compute coaptation area are restricted to indirect calculations using comparative measurements of full and uncoapted leaflet length at diastole and systole, respectively, or underestimate the true area by measuring only what is directly visible in rt-3DE images. Current intraoperative methods for assessing coaptation rely mainly on a measurement of coaptation length of at least 8 mm from rt-3DE imaging, which can not only be underestimated but also represents a simplistic one-dimensional geometric assessment of the complex coaptation behavior of the MV. Clearly, there is a need for a precise quantification of coaptation behavior using readily available clinical imaging data.
In the present study, we quantified the full 3D MV coaptation zone geometry before and after URA repair of MVs with IMR using clinically obtained rt-3DE images utilizing our MV shape-matching approach. This technique allowed us to fully resolve the MV coaptation zone into its contacting and redundant subregions. We then analyzed the functional impact of the repair at a level of detail currently not previously investigated, providing for a more nuanced understanding of the closing behavior of the regurgitant MV.

METHODS

2.1 Overview of the approach

An extant database of rt-3DE images of 14 IMR patient MVs from a previous study on MV strain before and after URA repair were analyzed. First, the images were segmented and processed, and the subsequent meshes were used as the inputs for our finite element (FE)-based closure simulation. In this simulation, the MV is initially closed by applying physiological loading and boundary conditions. Subsequently, a local corrective pressure field is applied to correct for shape mismatch and ensure the final shape of the MV closely corresponds to its true shape as segmented from the rt-3DE image. Extensive validation of this method confirms that this technique results in an accurate representation of the true, end-systolic (ES)-state MV, which is a significant improvement over the visualization limits of modern rt-3DE imaging. From this final closed mesh, the coaptation zone is subdivided into the contacting and redundant regions, and the areas of the leaflets and coaptation regions are computed and compared to better understand the impact of the ring implant on MV coaptation.

2.2 Shape-matching closure simulation

2.2.1 Imaging
Rt-3DE imaging was performed according to a previously described protocol immediately before and after URA repair in 14 patients with grade 3 or 4 IMR at the time of surgery. Each dataset captured 2-3 consecutive cardiac cycles with 6-12 frames per cycle at a voxel resolution of 0.6-0.8mm. Seven of the 14 patients had no recurrence of IMR 6 months post-repair, while the remaining 7 patients demonstrated recurrent IMR of grade 2 or higher at the same time point. Of the available data, only images with fully visible MV leaflets were used in this study. In the previous study from which these images were obtained, approval was granted by the Institutional Review Boards of the University of Pennsylvania, the University of Pittsburgh, and the Beth Israel Deaconess Medical Center, and written informed consent was obtained from all patients.

2.2.2 FE-based shape-matching method for planar strain estimation

The methods for this technique to estimate MV leaflet strain from rt-3DE images of patient MVs has been extensively detailed in. From the rt-3DE data series acquired of each patient’s MV immediately before and after URA repair, representative images in the open (end-diastolic) and closed (end-systolic) states were used to develop 3D shell representations of each geometry in a MATLAB-based tracing and meshing pipeline (Figure 1). To build direct material correspondence between the end-diastolic (ED) and ES states and to completely reconstruct the coaptation zone, we morphed the open state MV mesh to its corresponding closed shape using an FE based closure simulation (Figure 2). Our FE-based shape morphing technique has been previously described and extensively validated using both high-fidelity μCT data and in-vivo strain measurements. In both cases, the shape-morphing technique was able to reproduce the local strain field with excellent agreement to the in-vitro and in-vivo data and enforce the true closed shape of the MV as segmented from rt-3DE to within a signed intersurface distance of 0.035 ± 0.223 mm.
All shape-matching simulations were performed using the commercial FE software package Abaqus 6.13 (Dassault Systèmes).

2.3 Computing the coaptation area

The coaptation zone of the MV was subdivided into the contact area (the region where the two leaflets are in direct contact) and the redundant region (the portion of the leaflet which hangs below the free edge of the opposing leaflet) (Figure 3B). Contacting elements are defined as those with centroids within 0.8 mm (the voxel resolution) of each other, and with nearly antiparallel outward normals \( \mathbf{n}_a \) and \( \mathbf{n}_b \) for each respective element \( a \) and \( b \), such that \( \mathbf{n}_a \cdot \mathbf{n}_b \leq -0.98 \), where (Figure 3C). Redundant region elements were selected manually in ParaView (Kitware Inc.) by visualizing the valve from the positive and negative y axes and extracting all elements that were visible below the free edge of the other leaflet. Any elements which were identified as both contact and redundant were assigned to the contact set. To determine which elements corresponded to the anterior and posterior leaflets, the outward normal of each element was dotted with the unit y-normal vector; a positive dot product defined the anterior leaflet, and a negative dot product defined the posterior leaflet. Finally, the areas of the elements in each set were calculated and summed to compute the total area of that region.

2.4 Computing the MV tenting area

Central cross-sections (at \( x = 0 \)) were obtained for all 14 patients from the ES shape-matched geometries, and the mitral valve tenting area (MVTa) was computed by tracing the leaflets until the line of contact and calculating the area of the enclosed boundary. To calculate the 2D annular area, principal component analysis was used to align the annulus to the Cartesian coordinate system, and then the annulus was projected onto the z-plane and its enclosed area computed.
2.5 Statistical analysis

To quantitatively assess differences between groups of MVs, we performed one-tailed Student’s t-tests to compare the areas of the various coaptation zone regions across the nonrecurrent and recurrent groups, as well as the tenting area. Given that the pre-surgical and post-surgical MVs are repeated measures, we used paired one-tailed Student’s t-tests to analyze the change in area. A \( p \)-value of < 0.05 was considered statistically significant.

2.6 Validation

The shape-matching method has been carefully validated in previous work\textsuperscript{23}, but in this study, special attention was paid to the recovery of the coaptation zone shape. Given that the shape-matching method works by morphing the simulated mesh to the target geometry segmented directly from rt-3DE, we aimed to demonstrate that the technique can recover the coaptation zone even without having a complete end-systolic leaflet geometry to match, as limited in practice by ultrasound imaging. We used a previously extant set of 5 in-vitro ovine MV meshes as the target geometries for the shape matching. Briefly, freshly explanted ovine MVs were instrumented with ~100 fiducial markers uniformly distributed over the full MV surface area and installed into a pulsatile flow loop to mimic a healthy LV\textsuperscript{24}. The MVs were then imaged using a \( \mu \)CT scanner in both the ED (unloaded) and ES (fully loaded) states. This data was processed to reconstruct the ED leaflet geometry, and the end-systolic leaflet geometry was reconstructed by iteratively building correspondence between the fiducial markers in the two states within a hyperelastic FE framework.

These segmentations were used as the input for the shape-matching simulation. First, we morphed the ED leaflet geometry to the ES leaflet geometry using the shape-matching technique and calculated the contact region area and redundant region area as described in Section 2.3. To
mimic the incomplete coaptation zone as visualized on echo, we trimmed the coaptation zone at
the coaptation line in ParaView (Kitware Inc.) to produce the incomplete target geometry (Figure
4A). Then, we similarly morphed the ED leaflet geometry to this incomplete target using shape-
matching and re-calculated the contact and redundant region areas (Figure 4B). The values
computed from the simulations with and without a full coaptation zone were compared using one-
tailed Student’s t-tests.

RESULTS

3.1 Coaptation zone recovery

The shape-matching technique was able to fully recover the coaptation zone, which
normally is not visible in part or in full on ultrasound (Figure 5A, Video Abstract). Furthermore,
this method differentiates the coaptation zone into its subdivisions, which is an as yet
unprecedented level of geometric detail derived from rt-3DE images (Figure 5B). This more
precise insight into the closing behavior of the MV in both the diseased state and after URA repair
will deepen our understanding on the impact of the ring on the MV and may help contextualize
the divergent clinical outcomes among the patient groups.

3.2 Human undersized annuloplasty ring repair

Overall, we observed that after repair, recurrent MVs had larger coaptation area and
increased contact area compared to nonrecurrent valves (Figure 6B; \(p < 0.05\)). In this same group,
the redundant region also increased after repair (Figure 6C; \(p < 0.05\)). Additionally, we noted that
in all the patient MVs before and after repair, the majority of the redundant region is in the anterior
leaflet (Figure 6C).

Total systolic leaflet surface area decreased following surgical repair in both the
nonrecurrent and recurrent valves (Figure 6A; \(p < 0.05\)). Contact area increased more post-
surgically in the recurrent group (p = 0.0203, p > 0.05 for nonrecurrent), a trend which holds even when normalized to total systolic leaflet area to account for generally larger recurrent valves (Figure 7A; p = 0.0080, recurrent; p = 0.0401, nonrecurrent). The redundant region also increased post-surgically in recurrent valves (p = 0.0050, recurrent; p > 0.05, nonrecurrent), and again when normalized (Figure 7B; p = 0.0022, recurrent; p > 0.05, nonrecurrent). A general increase in contact area is expected in the context of URA repair, whose aim is to force increased coaptation by decreasing the size of the annulus and thus better approximating the leaflets. However, it is important to note that contrary to expectations, MVs with recurrence of IMR at six months have greater normalized contact immediately after repair. Therefore, improved contact may not be a reliable metric for determining durability of the repair.

While pre-surgical recurrent MVTa was significantly higher than nonrecurrent MVTa (p < 0.05), when normalized to measures of MV size using annular area or total systolic leaflet area, there was no longer a significant difference. After URA repair, there was no significant difference in absolute or normalized MVTa between the two groups (Table 1). This result suggests that MVTa was proportionally similar in both groups.

3.3 Validation with in-vitro fiducially marked ovine MVs

We observed no significant distortion in geometry when shape-matching to the full target compared to the clipped target geometry. This consistency is a direct consequence of the hyperelastic FE framework that we used to regularize the shape-matching simulation. The minimum impact on geometry was confirmed by computing and comparing the contact and redundant region areas between the final simulated geometries when shape-matching to a complete or incomplete target. We found no significant difference between these two metrics (p > 0.1) for both the contact and redundant region areas) (Figure 4B). These results demonstrate that the shape-
matching technique reliably reconstructed the MV coaptation zone even when the coaptation zone is incomplete or missing, which is a major limitation of echocardiographic imaging.

DISCUSSION

4.1 Overall findings

Given that the fundamental functional basis of MV regurgitation is insufficient leaflet coaptation, one of Carpentier’s guiding principles for MV repair is that increasing coaptation area leads to a more durable repair \(12\). However, despite advances in annuloplasty and other repair techniques which aim to improve leaflet coaptation, recurrent MR continues to persist as a major clinical challenge in MR treatment \(2,18,25\). Furthermore, though real-time echocardiography is a standard clinical tool in assessing MV function, a significant limitation of this imaging modality is that it cannot entirely resolve the crucial coaptation zone in the systolic position. Therefore, we aimed to reconstruct the coaptation zone using our state-of-the-art shape-matching technique, then to directly compute the associated areas at a high level of detail before and after surgical URA repair.

We found paradoxically that in patients that develop recurrent IMR six months after URA repair, the contact area immediately after repair was greater than that of patients who did not have recurrent MR at six months (Figure 6B). Moreover, when normalized to total systolic leaflet area to account for generally larger pre-surgical MVs in the recurrent group, the contact area increased more in the recurrent group compared to the nonrecurrent group (Figure 7A). The redundant region is also significantly greater in recurrent patients, even when normalized (Figure 7B).

These observations can be explained by the fact that all patients received approximately the same sized annuloplasty ring. As the recurrent MVs had significantly larger pre-repair annuli compared with the nonrecurrent MVs, using the similarly sized rings resulted in very similar post-
surgical annular orifice areas for both groups. Therefore, recurrent MVs experienced a greater percent change in annulus reduction post-repair. Consequently, the recurrent MVs are likely much more tethered after repair than their nonrecurrent counterparts, which may explain the suboptimal long-term outcomes for this group. Moreover, for the recurrent MVs, more leaflet tissue was shunted into the coaptation zone, increasing both contact and redundant region area for this subset. This shunting of tissue into the coaptation zone may also explain why total systolic leaflet area decreases after URA repair in both nonrecurrent and recurrent MVs (Figure 6A). LV pressurization acts normal to the MV leaflet surface, and in the systolic position, pressurization in the coaptation zone of one leaflet is directly counterbalanced by equal and opposite pressurization on the other leaflet. Consequently, only leaflet tissue outside the coaptation zone can be deformed (i.e., stretched) by LV pressurization. After URA repair, as more leaflet tissue is shunted into the coaptation zone, there is less available deformable leaflet tissue compared to the pre-surgical state, and hence, the total systolic leaflet surface area decreases.

Furthermore, our analysis of the MVTa demonstrated that while there is a significant difference in measured values between pre-surgical nonrecurrent and recurrent ES MVTa, this difference disappears when MVTa were normalized to measures of MV size (Table 1). As a larger MV can be related to more advanced LV dilatation or simply larger patient size, MVTa may not necessarily reflect a more severe presentation of IMR. Though several studies have pointed to MVTa as a prognostic factor of clinical outcome, a study analyzing annular antero-posterior diameter-indexed MVTa in FMR patients undergoing URA repair showed only a tendency towards prediction of clinical outcome. Therefore, these results and those regarding the coaptation zone suggest that MV geometric indices may be insufficient to reliably assess the complex kinematic sequelae of IMR which crucially influence repair outcomes.
In addition, we have also demonstrated in this study the utility of our shape-matching technique in recovering the full coaptation zone, which remains critical for assessing the functional behavior of the valve but can be underestimated in rt-3DE imaging (Figure 5A). Moreover, we were able to further distinguish this zone into its contacting and redundant sub-regions and separate these by leaflet (Figure 5B). Such a level of detail is not presently possible to acquire with imaging alone and will allow us to refine our understanding of normal and regurgitant MV behavior, as well as the functional consequences of available repair techniques.

4.2 Clinical implications

Importantly, these findings suggest that greater MV coaptation area alone may not necessarily indicate a more durable repair. These results suggest that in recurrent IMR patients, continued LV remodelling may be the primary driving mechanism behind the regurgitation rather than the MV itself. Previous studies have extensively shown that preoperative LV dilatation and remodelling are associated with, and even predictive of, MV recurrence after URA repair. Giammarco et al. demonstrated in a retrospective study of patients with dilated cardiomyopathy and MR that LVEDV was predictive of recurrence after URA repair regardless of MR etiology. Gelsomino et al. also found that pre-operative LV global remodelling played a central role in predicting recurrence, with preoperative LVESV as one such metric. Furthermore, they observed significant continued global LV remodelling after URA repair, which Hung et al. showed is associated with MR recurrence. Recent analyses regarding divergent outcomes of percutaneous repair have also pointed to the dilatation of the LV in relation to the preoperative MR grade as a possible explanation for why patients with larger LVs tend to have poorer outcomes than patients with smaller LVs but equally severe MR. Consequently, an MV-directed treatment approach such as annuloplasty, even though it corrects the faulty coaptation behavior of the MV, may not
be a durable choice in this subset of patients. Therefore, a deeper understanding is necessary regarding the functional interrelationship between the diseased LV and the MV.

In addition to the remodeling of the LV, the MV leaflets themselves may have undergone more advanced adverse remodeling in recurrent patients. Previous work has shown that presurgical strain in MV leaflets differs substantially between the nonrecurrent and recurrent patient groups, to the point that presurgical circumferential strain in the A1 segment can act as a reliable predictor of recurrence six months after URA repair. We have also demonstrated in an ovine IMR model that MV leaflets undergo irreversible isotropic plastic deformation by 8 weeks post-MI with dramatic changes in radial extensibility, and that these changes were driven by permanent radial distension, not damage to collagen fibers. Moreover, these tissue-level observations were associated with underlying changes in transcriptomic responses. Therefore, methods to restore normal valve function may ultimately prove unsuccessful in patients whose MV leaflets have been plastically distorted by the disease process, and that aiming to place the MV in an alternative homeostatic state may be a more sustainable option.

4.3 Limitations

While we found key statistical differences in the coaptation patterns of the nonrecurrent and recurrent MVs after URA repair, our analysis was limited to 14 IMR patients. Therefore, our findings may not reflect variations in a larger population that includes degenerative MR or mixed MR etiologies, though the same techniques can be applied to similarly study patients with other types of MR. Continued adverse LV remodeling after repair, as well as the relation between MR severity and LV size have been shown to play a role in repair durability, so future studies should be directed towards the development of an integrated LV-MV model, which will allow us to characterize the functional impact of left ventricular pathologies on MV mechanics.
The current study applied a simulation-based technique to recover the full MV geometry from clinically obtained echocardiographic images, which demonstrated that contrary to expectations, increased MV leaflet coaptation after URA repair does not necessarily imply a more durable repair. These findings implied that in this recurrent subgroup, adverse LV remodeling, aggravated leaflet tethering, and/or advanced leaflet plasticity may play a larger role in the MR disease process, suggesting that MV-focused treatments alone may not lead to optimal outcomes.

ACKNOWLEDGEMENTS

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REFERENCES


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Table 1: Computed absolute end-systolic MVTa and normalized MVTa (to annular area and total systolic leaflet area) for the nonrecurrent and recurrent MVs before and after URA repair. MVTa: mitral valve tenting area; URA: undersized ring annuloplasty
LEGENDS

**Figure 1:** A noninvasive simulation-based method was used to quantify the coaptation zone area from rt-3DE images. Results demonstrated that post-surgical coaptation zone area was greater in patients with recurrent IMR at six months compared to patients without recurrence (p < 0.05). The contacting region area (where the two leaflets are in direct contact) was also greater in recurrent patients, even when normalized to total systolic leaflet area to account for generally larger recurrent MVs. Rt-3DE: real-time three-dimensional echocardiography; IMR: ischemic mitral regurgitation; MV: mitral valve

**Figure 2:** The progression of the FE closure simulation from the open state to the final, shape-matched closed state. (A) The central cross-sections showing the simulated geometry at the beginning of the simulation, after the initial FE closure, and after applying the LCPF to enforce the true imaged shape. Red: central cross-section of the imaged closed state leaflet medial surface. Grey: the open segmented geometry of the MV, which is the input to the simulation Black: central cross-section of the simulated geometry. (B) The 3D meshes corresponding to the cross-sections in (A) showing the simulated geometry (grey) and true, imaged closed state geometry (red) at the same time points. FE: finite element; LCPF: local corrective pressure field; MV: mitral valve

**Figure 3:** (A) A representative MV with the coaptation sub-regions colored. (B) A cross-section of the representative MV illustrating the two leaflets, and the contact region, where the leaflets are physically in contact, and the redundant region, where tissue from one leaflet extends past the free edge of the opposing leaflet. (C) An example of two contacting elements (highlighted in blue). The distance between the two centroids is at most 0.8 mm, and the dot product of their outward normal vectors is at most -0.98, indicating nearly antiparallel elements. MV: mitral valve; AL: anterior leaflet; PL: posterior leaflet
Figure 4: (A) The full target closed geometry of a representative MV, and a cross-section showing the clipped target, which excludes the coaptation zone. (B) The contact and redundant region areas were calculating from the final simulated geometries matched to targets with and without the full coaptation zone, and there was no significant difference between the measures. MV: mitral valve.

Figure 5: (A) The open and closed geometries, as well as the simulation output, for a representative recurrent valve. The simulation is able to recover a large portion of the coaptation zone, which is not visible on the rt-3DE image but can be reconstructed from the fully visible open leaflet geometry. (B) A representative nonrecurrent and recurrent MV before and after URA repair shown in 2D, with the elements of each coaptation region highlighted. Rt-3DE: real-time three-dimensional echocardiography; AL: anterior leaflet; PL: posterior leaflet.

Figure 6: (A) Total systolic leaflet area grouped before and after URA repair in nonrecurrent and recurrent MVs. Before surgery, the recurrent MVs are larger than the nonrecurrent MVs (p = 0.0156). (B) The total coaptation zone divided into its two main regions--contact and redundant--for nonrecurrent and recurrent MVs, pre- and post-repair. Standard errors and significance are shown for the full coaptation zone. The coaptation zone increases significantly in recurrent MVs (p = 0.0051). (C) The redundant region divided by leaflet in nonrecurrent and recurrent MVs pre- and post-repair. Standard errors and significance are shown for the full redundant region. The majority of the redundant region lies on the anterior leaflet, and the redundant region in recurrent MVs increases significantly post-repair (p = 0.0050). URA: undersized ring annuloplasty; MV: mitral valve.

Figure 7: (A) Contact region area normalized to total systolic leaflet area. While the normalized contact area increases after repair in both groups, the recurrent MVs show a greater increase (p =
0.0080, recurrent, compared to $p = 0.0401$, nonrecurrent). (B) Redundant region area normalized to systolic leaflet area. The normalized redundant region increases significantly in recurrent MVs, whereas in nonrecurrent MVs, it stays relatively similar. MV: mitral valve

**Video Legend:** Quantification of MV coaptation behavior after URA repair in IMR patients using rt-3DE-based computational modeling. MV: mitral valve; URA: undersized ring annuloplasty; IMR: ischemic MR; rt-3DE: real-time 3D echocardiography
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**Image-based reconstruction of full coaptation zone**

- **r-3DE Data Series**
  - n = 7 non-recurrent MR
  - n = 7 recurrent MR

- **Segmentation and processing**
- **Open state mesh**
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- **Shape-Matching Method**

- **Recovery of full systolic coaptation zone**

**Post-repair coaptation area increases more in recurrent patients**

- **Coaptation Zone Area**
  - Non-recurrent
  - Recurrent

- **Contact Area Normalized to Total Systolic Area**
  - Non-recurrent
  - Recurrent

**Surgical Implications**

- Coaptation area alone may not be a reliable target for repair durability
- In some patients, adverse LV remodeling, aggravated leaflet tethering, and/or advanced leaflet plasticity may play a larger role in the MR disease process
- MV-focused repair may not lead to optimal outcomes in this patient subgroup
- Patient-specific and LV/MV integrated models are crucial for improved treatment planning

**Abbreviations**

- r-3DE: real-time three-dimensional echocardiography
- MR: mitral regurgitation
- LV: left ventricle
A

In vitro ovine closed state geometry

B

Shape-Matching to Incomplete Coaptation Zone

CONTACT REGION

REDUNDANT REGION

\[ p = 0.3527 \]

\[ p = 0.4275 \]
Quantitative In-Vivo Assessment of Human Mitral Valve Coaptation Area After Undersized Ring Annuloplasty Repair in Ischemic Mitral Regurgitation

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