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Residual stress impairs pump function after surgical ventricular remodeling: A finite element analysis

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Abstract

Objectives—Surgical ventricular restoration (Dor procedure) is generally thought to reduce left ventricular (LV) myofiber stress (FS) but to adversely affect pump function. However, the underlying mechanism is unclear. The goal of this study was to determine the effect of residual stress (RS) on LV FS and pump function after the Dor procedure.

Methods—Previously described finite element models of the LV based on MRI data obtained in five sheep 16 weeks after antero-apical myocardial infarction were used. Simulated Dacron patches that were elliptical and 25% of the infarct opening area were implanted using a virtual suture technique (VIRTUAL-DOR). In each case, diastole and systole were simulated and RS, FS, LV volumes, systolic and diastolic function, and pump (Starling) function were calculated.

Results—VIRTUAL-DOR was associated with significant RS that was tensile (2.89 ± 1.31 kPa) in the remote myocardium and compressive (234.15 ± 65.53 kPa) in the borderzone (BZ). VIRTUAL-DOR+RS (compared to VIRTUAL-DOR-NO-RS) was associated with further reduction in regional diastolic and systolic FS with the greatest change in the BZ (43.5-fold and 7.1-fold respectively, $p < 0.0001$). VIRTUAL-DOR+RS was also associated with further reduction in systolic and diastolic volumes (7.9%, $p = 0.0606$ and 10.6%, $p = 0.0630$, respectively). The resultant effect was a further reduction in pump function after VIRTUAL-DOR+RS.

Conclusion—Residual stress that occurs after the Dor procedure is positive (tensile) in the remote myocardium and negative (compressive) in the BZ and associated with reductions in fiber stress and LV volumes. The resultant effect is a further reduction in LV pump (Starling) function.

Keywords

Heart failure; Myocardial Infarction; Surgery; Modeling (Finite Element)

Introduction

Initially described by Dor in 1989 [1], Surgical Ventricular Remodeling (SVR: Dor procedure) is used to reduce left ventricular (LV) volume and myofiber stress (FS) after myocardial infarction. Briefly, a patch of either autologous or synthetic material is sewn to the edge of the aneurysm neck thereby reducing LV volume. [1] The Dor procedure is proposed to reduce post-infarct LV remodeling and heart failure.

Unfortunately, the Dor procedure is generally thought to adversely affect pump function. [2] For instance, the NIH-sponsored Surgical Treatment for Ischemic Heart failure trial found no difference in composite outcome between coronary bypass and coronary bypass plus SVR procedure. [3] The authors speculated that improved systolic function was balanced by worsened diastolic function. [3]

Residual stress is stress that remains when pressure in the LV cavity is zero. [4] As such, there are two instances of residual stress that must be considered in an analysis of the Dor procedure. The first is the residual stress that may exist in the remodeled ventricle prior to surgical restoration. In this case, residual stress, which is present in the normal rat ventricle [5], is thought to be decreased in the dilated LV.

The second instance of residual stress is the stress that is imparted by the surgical procedure. In this case, an increase in residual stress was hypothesized by Kresh and Wechsler to be a mechanism whereby pump function was improved after SVR. [6] However, a prior study by Guccione et al found that residual stress had minimal effect. [7] On the other hand, a more recent finite element simulation of the Coapsys device, a trans-LV Gortex chord intended to treat ischemic mitral regurgitation, by Carrick et al found that knowledge of residual stress in the LV was necessary for accurate calculation of LV myofiber stress. [8] That study prompted us to reconsider the effect of residual stress after SVR.

Finite element modeling of the heart and cardiac surgical procedures is becoming more common. [9, 10] For instance, Sun et al previously used models of the LV based on sheep with antero-apical myocardial infarct that were studied before and after Dor procedure to determine the effect on myofiber stress and contractility in the infarct borderzone (BZ). [11] Although myofiber stress was reduced, BZ contractility did not improve. [11]

The goal of this study was to determine the role of residual stress on post-operative myofiber stress and LV pump function. We tested the hypothesis that residual stress significantly effects myofiber stress and Starling function after the Dor procedure.

Methods

Finite Element Model

Animals used in this study were treated in compliance with the “Guide for the Care and Use of Laboratory Animals.” Five sheep underwent antero-apical myocardial infarct. [12] Magnetic resonance imaging obtained 16 weeks after myocardial infarct was used to create three finite element models for each animal—PRE-OP, VIRTUAL-DOR with residual stress

(VIRTUAL-DOR+RS), and VIRTUAL-DOR without residual stress (VIRTUAL-DOR-NO-RS). The PRE-OP finite element models were previously described. [11]

Dor procedure simulations were created by first simulating the application of a patch to the PRE-OP model. Patch area was approximately 25% of the infarct neck area equating to the standard 50% reduction in infarct neck diameters parallel to the basal plane in the anterior-posterior and septal-lateral directions. Using a previously described method [13], virtual sutures were applied approximately perpendicular between the edge of the patch and the endocardium (Figure 1A, 1B) and tightened with a contracting force mechanically bringing the endocardium and patch edges together (Figure 1C). Diastole and systole were then simulated by loading the endocardium to measured in-vivo end-diastolic and end-systolic LV pressures (LS-DYNA, Livermore Software Technology Corporation, Livermore, CA).

The VIRTUAL-DOR+RS model assumes that the pre-op unloaded diastolic state prior to patch application is the stress-free state. The VIRTUAL-DOR-NO-RS model assumed that the reshaped LV after patch application and immediately before diastolic filling was the initial unloaded reference state.

In the VIRTUAL-DOR cases, the diastolic and systolic material parameters, C and T_{max} , matched the pre-op values to isolate the acute effects of residual stress prior to any ventricular remodeling. These pre-op myocardial material properties were optimized as previously described by Sun et. al [14].

The BZ-infarct boundary was defined manually and the BZ-remote boundary was defined as the point where wall thickness is 70% of the maximum wall thickness. Lastly, the boundary between the near BZ and far BZ is the midline that bisects the BZ region. [14]

After each simulation average regional and residual stresses (RS) in the remote myocardium and BZ were calculated. RS in diastole was FS at the start of diastolic filling (LV pressure = 0). Systolic RS was the difference between FS at end-systole with LV pressure = 0 minus the effect of active contraction.

The mesh density used in these models was previously optimized to balance accuracy and computational resources with a mesh convergence study. [23] However, to ensure the accuracy of this mesh density in measuring the effect of RS, the current mesh was refined to twice and three times the density and regional stresses at each mesh refinement were compared.

Pump Function Parameters

To assess pump function, pressure-volume relationships at end-diastole (EDPVR) and end-systole (ESPVR) were calculated by varying end-diastolic pressure from 1mmHg to 20mmHg or end-systolic pressure from 1mmHg to 100mmHg and simulating a cardiac cycle. The resulting end-diastolic pressure volume data was fitted to

$$P=Ae^{BV}+C$$

where A, B, and C are fitting parameters and A and B determine the LV diastolic compliance. The end-systolic pressure volume data was fitted to

$$P = A_{ES} V + B_{ES}$$

where A_{ES} (LV elastance), and B_{ES} , are fitting parameters. Lastly, the Starling curve was created by estimating the stroke volume within an end-diastolic pressure range of 1mmHg to 20mmHg. Stroke volume was calculated using the following equation:

$$SV = \frac{(V_{ED} - V_0)}{(1 + \frac{E_A}{A_{ES}})}$$

where V_{ED} is the end-diastolic volume at a given end-diastolic pressure as estimated by EDPVR, V_0 is the volume intercept of the ESPVR ($-B_{ES}/A_{ES}$), E_A is the arterial elastance calculated at in-vivo end-diastolic and end-systolic pressures. Finally, the data was fitted to the following equation:

$$SV = S_1 P^2 + S_2 P + S_3$$

where S_{1-3} are the fitting parameters.

Statistical analysis

All values are expressed as mean $\pm$ standard deviation and compared by repeated measures analysis using a mixed model using SAS PROC MIXED (SAS system for Windows Version 9.1, SAS Institute, Cary, NC). Individual sheep were treated as a random variable. The impact of RS on regional FS, LV volumes, and each curve-fitting parameter (specified above) were tested by comparing PRE-OP to VIRTUAL-DOR cases with and without RS. Significance was set at p less than 0.05.

Results

Calculated residual stress at end-diastole and end-systole caused by VIRTUAL-DOR is seen in Table 1. VIRTUAL-DOR was associated with significant RS that was tensile in the remote myocardium and compressive in the BZ.

VIRTUAL-DOR+RS was associated with further reduction in regional diastolic and systolic FS with the greatest change in the near BZ when compared to VIRTUAL-DOR-NO-RS (Tables 2 and 3). Specifically, VIRTUAL-DOR-NO-RS is associated with a significant reduction in FS in the remote myocardium (-17.9% $p=0.0359$). However, VIRTUAL-DOR+RS is associated with a greater reduction in FS (compression) in the near BZ (43-fold reduction; $p<0.0001$) and a trend toward reduction in FS at end-diastole from the far BZ (-199.2% , $p=0.0122$) towards the remote myocardium (-24.1% , $p=0.0234$).

The effect of RS on FS at end-systole follows a similar pattern. VIRTUAL-DOR-NO-RS is associated with significant reductions in the far BZ (-32.3% $p=0.0276$) and remote

myocardium (-6.5% $p=0.0018$). However, in the VIRTUAL-DOR+RS simulation there is a greater reduction in FS in the near BZ (7-fold decrease, $p<0.0001$) and a trend toward reduction in FS at end-systole in the far BZ (-79% , $p=0.0025$) towards the remote myocardium (-8.7% $p=0.0001$).

Mesh refinement and model predictions

Upon successive mesh refinement, there was no significant change in FS or LV volumes (Figure 2). In the remote myocardium the largest change with the finest mesh was 1.01 kPa at end-diastole. In the near BZ there was an average 12.48kPa difference with the finest mesh. However, average end-systolic stresses were variable with successive mesh refinement with a 3% difference at the finest mesh. Mesh refinement did not significantly change LV volume calculations. Thus, coarse mesh was used for the analysis of this experiment.

Effect of residual stress on pump function

VIRTUAL-DOR+RS was also associated with further reduction in systolic and diastolic volumes and function (Figure 3). Both VIRTUAL-DOR simulations with and without RS shift the ESPVR curve to the left. However, elastance after VIRTUAL-DOR+RS was 5 times higher than PRE-OP ($19.44\pm 11.31\text{mmHg/mL}$ vs $3.92\pm 0.7\text{mmHg/mL}$, $p=0.0034$) while elastance after VIRTUAL-DOR-NO-RS was 2.5 times higher than PRE-OP ($7.79\pm 2.92\text{mmHg/mL}$, $p=0.0149$).

Both VIRTUAL-DOR simulations with and without RS also decreased LV diastolic compliance, evidenced by the leftward shifted and steeper post-op diastolic curves (Figure 4). However, the effect on diastolic LV volume and function was greater than that in systole leading to a subsequently greater reduction in pump function with VIRTUAL-DOR+RS (Figure 5).

VIRTUAL-DOR+RS models had an average leftward volumetric shift in EDPVR of $25.85\pm 2.49\text{mL}$ while the average volumetric shift in ESPVR was $4.27\pm 2.39\text{mL}$, compared to VIRTUAL-DOR-NO-RS. Larger effects on diastolic function, lead to a depression in Starling function. VIRTUAL-DOR-NO-RS reduced the vertical stretch coefficient A by 50% and vertical shift coefficient B by 40% ($p=0.0123$, $p=0.0028$). VIRTUAL-DOR+RS added additional 300% reduction in A and 40% reduction in B ($p=0.0009$, $p=0.0001$). This combined reduction in starling coefficients flattened and shifted the starling curves downward. Nonetheless, at actual end-diastolic pressures of 10.21mmHg, there was no significant difference in actual stroke volume between the models (Table 4).

Discussion

The principal finding of the study is that residual stress that occurs after the Dor procedure is positive (tensile) in the remote myocardium and negative (compressive) in the BZ and associated with reductions in fiber stress and LV volumes. The resultant effect is a further reduction in pump (Starling) function with VIRTUAL-DOR+RS.

Our previous simulations of the Dor procedure [11] and adjustable passive LV constraint [15] assumed that the ventricular wall is stress-free at the time of early diastolic filling. In contrast, the VIRTUAL-DOR simulation was applied to the unloaded PRE-OP model thereby imparting RS to the ventricular wall. The difference in FS, pressure-volume relationships and pump function between the VIRTUAL-DOR simulations with and without RS clearly demonstrates the effect of RS after ventricular reconstruction.

Effect on diastole and pump function

In both VIRTUAL-DOR simulations with and without RS there was a larger leftward shift in EDPVR than in ESPVR and a resultant reduction in pump function. The addition of RS increases the leftward volume shift in EDPVR and further reduces pump function. These findings are in-line with clinical reports that show a relationship between diastolic compliance and outcomes after the Dor procedure. [16–18] Diastolic compliance appears to be reduced early after SVR leading to a reduction in stroke volume [16, 18] and patients with pre-op diastolic dysfunction may have worse outcome after surgical remodeling. [16, 17]

RS in the remote myocardium is positive while the RS in the BZ is negative (compressive). These findings are in line with a study of aneurysm plication in sheep by Savage and colleagues. [19] That study, which used a sonomicrometry array to determine the acute effects of plication on LV geometry, found an increase in longitudinal strain in the remote anterior wall and a decrease in regional BZ compliance.

We suggest that the effect on diastolic compliance and resultant effect on pump function is explained by the shape of the passive and active stress-strain relationships of the myocardium under tension and compression (Figure 6). [20] Since the passive or diastolic stress strain curve is non-linear, the addition of tensile RS to the remote myocardium, as for example moving from point A $\rightarrow$ A', will cause a greater change in stress per incremental increase in strain. In contrast, the systolic stress-strain curve is linear and the addition of tensile RS to the remote myocardium (B $\rightarrow$ B') has no effect on the change in stress per strain.

The effect of compressive RS in the BZ is less clear. First, although the mechanical effect of compression on myocardium has not been measured, there is data showing how skeletal muscle behaves under compression [21] and the behavior of the Guccione passive myocardial material property law under compression (Figure 6, Blue line where strain < 0) [22] is similar to the experimental data from skeletal muscle (not shown). As seen in the figure, the passive compression relationship curves slightly downward as strain becomes more negative. Therefore, the addition of compressive RS to the BZ (C $\rightarrow$ C') will move the BZ myocardium to a steeper part of the curve. However, the mechanical effect is probably small and we conclude that the predominant effect of RS is the addition of tensile RS to the remote myocardium.

Residual stress generation in other operations and devices

We contend that knowledge gained about the mechanical effect of the Dor procedure from our study will have application beyond the limited scope of the Dor procedure. We have

previously looked at the effect of RS in the Cardiokinetix and Coapsys devices. [7, 8] However, there may be many more operations and devices that impart RS including congenital heart surgery including Tetralogy of Fallot repair and mitral valve repair methods including mitral annuloplasty, papillary muscle relocation etc. The augmentation of RS is inherent to the surgical reconstruction process and investigations into its mechanical implications will add to our understanding of cardiac surgical interventions.

The findings in the current study are consistent with our previous finite element simulation of partial ventriculectomy [7] and Coapsys [8] although the effect of RS in the Dor procedure is larger than that found in the other studies. We suggest that the change in LV geometry imposed by the Dor procedure is more extreme than that imposed by partial ventriculectomy and the Coapsys device. The Dor procedure excludes the entire infarct and reduces the neck of the aneurysm by 75% imposing large RS at the near BZ. In contrast, the other procedures distribute a small shape change over the entire myocardium thereby distributing the mechanical effects of RS throughout the myocardium. Additionally, the PRE-OP model in these studies differed in mechanical properties and pathology from that used in the present study.

Study Limitations

The lack of knowledge of corroborating experimental data early after SVR in the operating room is a significant limitation. Such data might include measurement of myocardial deformation in the region adjacent to the surgical patch to confirm myocardial compression. [23]

Further, we assumed the passive stress-strain relationship of cardiac walls in the negative strain area is symmetric to that of the positive strain region. There is evidence suggesting this is not the case. For instance, muscle fibers tend to buckle under compressive load and therefore may not support large amounts of compression. [24] We are currently implementing mathematical models for the cardiac walls to account for such effects. Revising the passive material model could lead to smaller compressive stress in the areas near the sutures but is unlikely to change the conclusions of this work. Finally, the models assume that end-diastole is a stress free state and do not incorporate RS that are inherent prior to the Dor procedure.

Conclusions

Residual stress that occurs after the Dor procedure is positive (tensile) in the remote myocardium and negative (compressive) in the BZ and associated with reductions in fiber stress and LV volumes. This change may persist after post-surgical LV remodeling and may contribute to the lack of clinical benefit. This study demonstrates the power of the virtual suture method in the understanding of surgical procedures.

Future work includes the measurement of RS with experimental and computational methods. Further, it is an open question whether variations in patch size and shape or operations designed to produce a more elliptical LV will have the same effect on diastole.

Acknowledgments

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Appendix

Table A1

Left ventricular regional material parameters.

	Remote passive stiffness (C)	Near Borderzone contractility (Tmax_BZ1)	Far Borderzone contractility (Tmax_BZ2)	Remote Myocardium contractility (Tmax_R)
All Finite Element Models	1.035±0.373	831.48±447.75	1272.89±493.32	5304.58±4364.94

VIRTUAL-DOR parameters matched PRE-OP parameters to isolate acute effects of residual stress.

Table A2

Effect of the Dor procedure on left ventricular pressure-volume relationships where $P=Ae^{(BV)}+C$ models the end-diastolic curve and $P=A_{ES}V+B_{ES}$ models the end-systolic curve.

	End-Diastolic Coefficient A	End-Diastolic Coefficient B	End-Systolic Coefficient A _{ES}	End-Systolic Coefficient B _{ES}
Finite Element Model: PRE-OP	0.818±0.450	0.0309±0.00658	3.920±0.696	-326.257±48.689
VIRTUAL-DOR+RS	15.739±22.031	0.0412±0.0310	19.439±11.313*	-915.567±441.363*
VIRTUAL-DOR-NO-RS	5.927±4.655	0.0317±0.0159	7.792±2.916 [†]	-370.362±78.095 [†]

* = p<0.05 with respect to PRE-OP,

[†] = p<0.05 with respect to VIRTUAL-DOR+RS.

Table A3

Effect of Dor on left ventricular starling relationship where $SV=S_1P^2+S_2P+S_3$ models the starling curve.

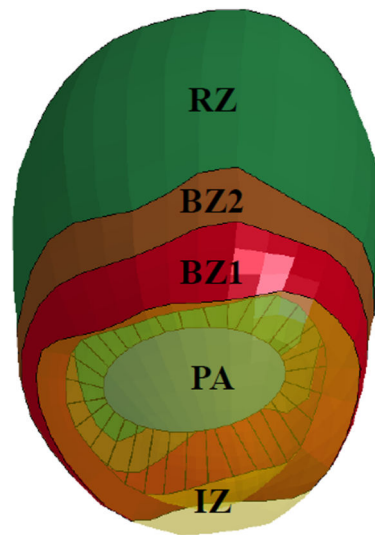
	Starling Coefficient A	Starling Coefficient B	Starling Coefficient C
Finite Element Model: PRE-OP	-0.0235±0.0190	1.243±0.628	12.347±4.813
VIRTUAL-DOR+RS	-0.00396±0.00729 [*]	0.520±0.362 [*]	8.319±3.165 [*]
VIRTUAL-DOR-NO-RS	-0.0111±0.0128 ^{*‡}	0.806±0.497 ^{*†}	9.900±3.699

^{*} = p<0.05 with respect to **PRE-OP**,

[†] = p<0.05 and

[‡] =p<0.1 with respect to **VIRTUAL-DOR+RS**.

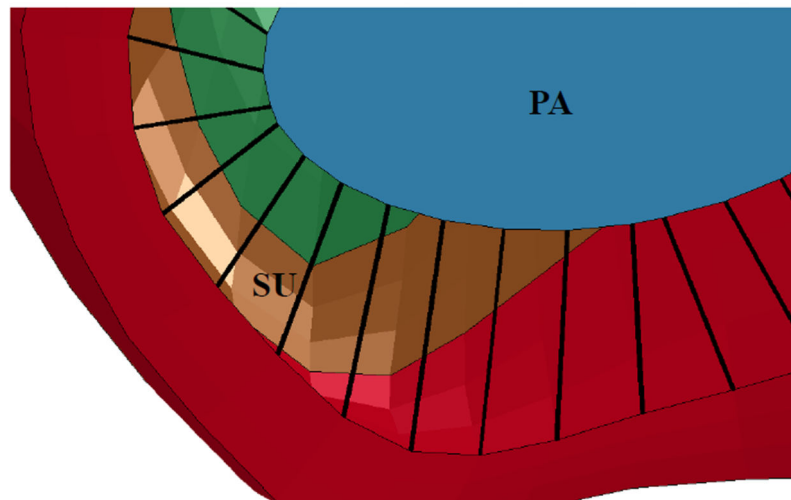
A.



B.



C.

**Figure 1.**

VIRTUAL-Dor procedure using virtual sutures. (A) Virtual sutures (black) are attached to the edge of the patch (blue) and endocardium at each of the 32 node points. (B) The LV after virtual sutures are tightened. (C) An expanded view of virtual sutures. PA= patch (blue), SU= sutures (black), IZ= infarct zone (transparent yellow), BZ1= near borderzone (red), BZ2 = far borderzone (brown), RZ = remote myocardium (green).

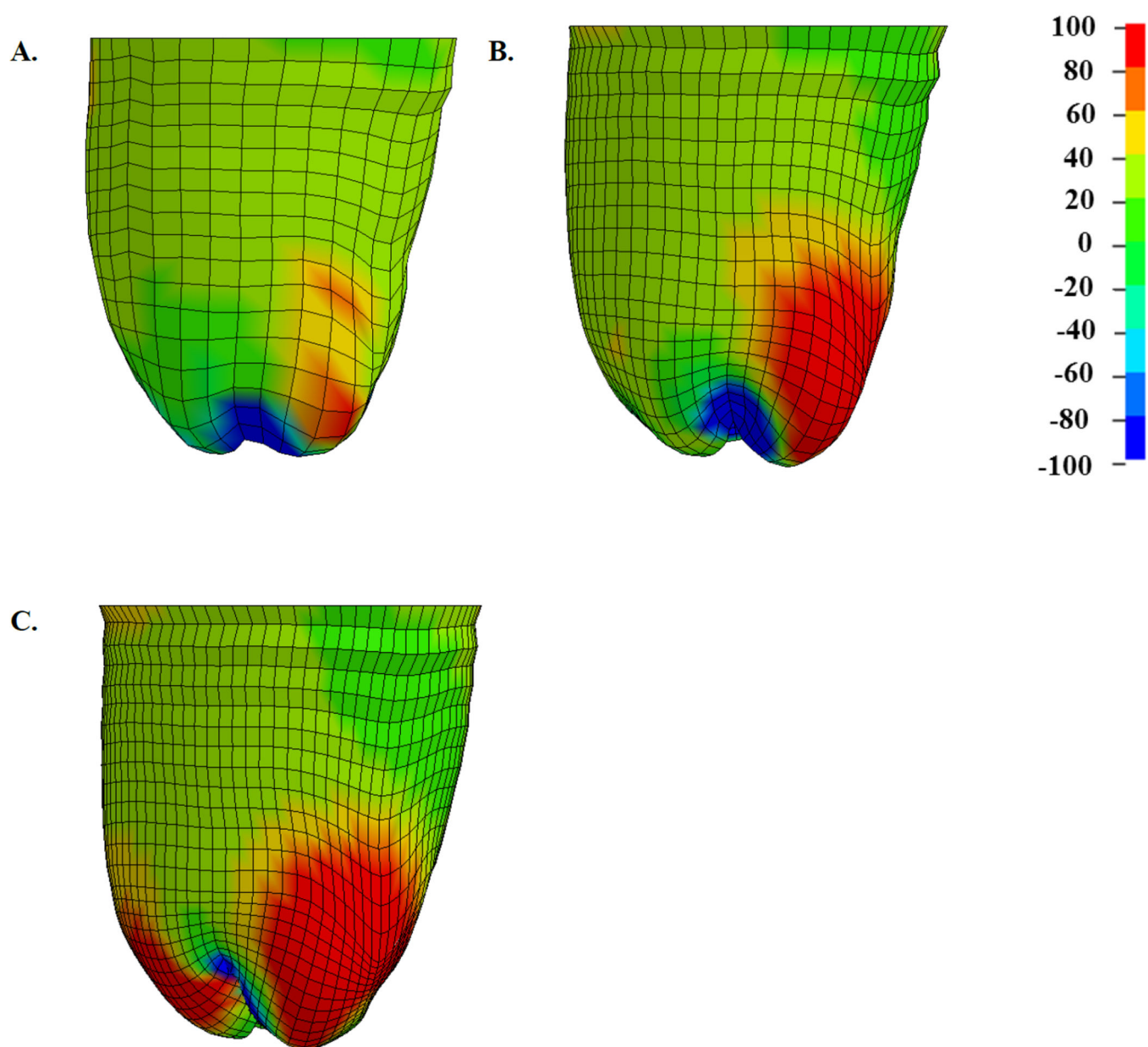


Figure 2. Surface plot of fiber stress at end-systole with (A) optimized mesh and successive mesh refinements at (B) two times and (C) three times the mesh density with respect to the optimized mesh

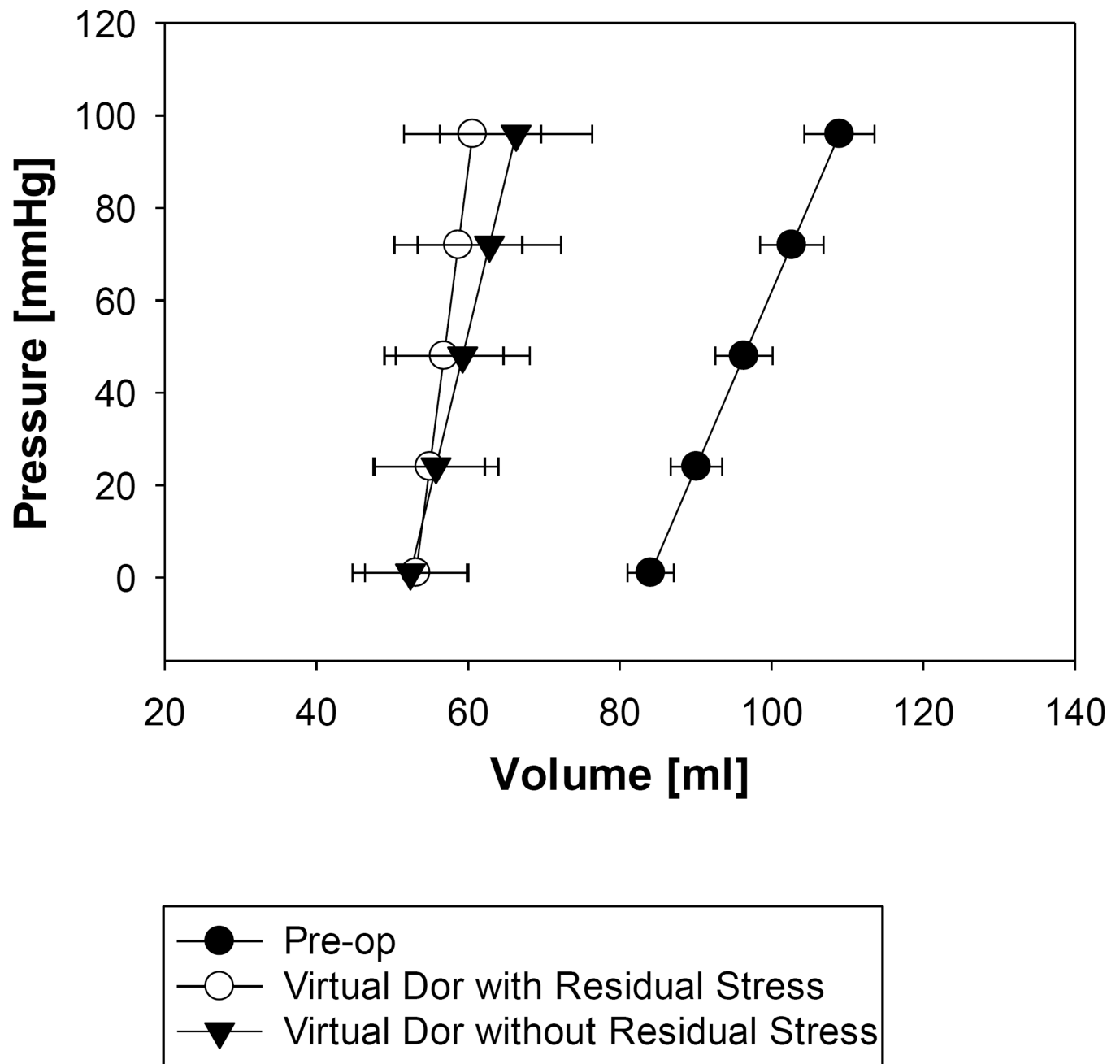


Figure 3.

Average end-systolic pressure-volume relationship linear-fit to $P = A_{ES}V + B_{ES}$ where A_{ES} and B_{ES} are linear fit parameters

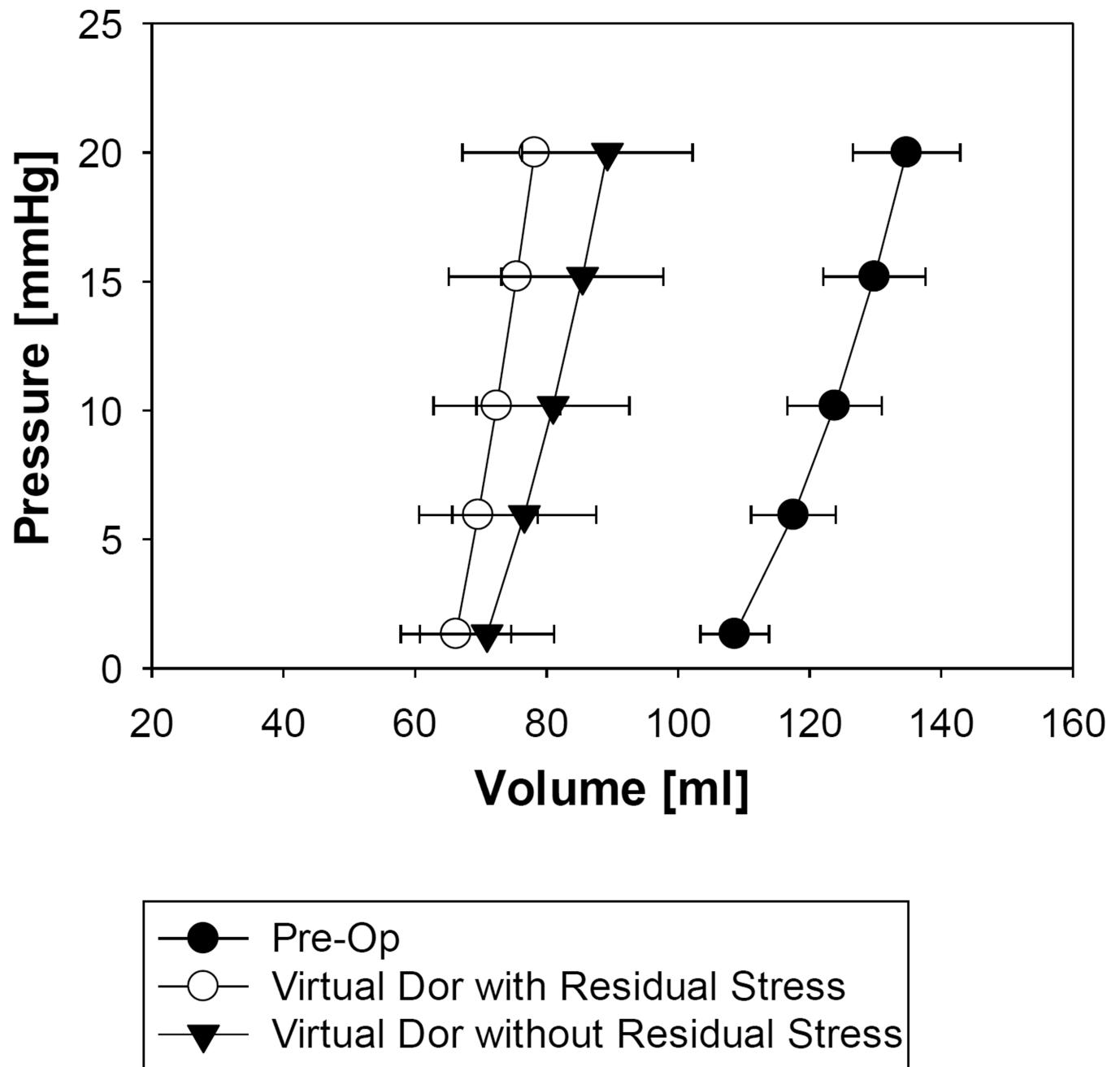


Figure 4.

Average end-diastolic pressure-volume relationship curve-fit to $P=Ae^{(BV)}+C$ where A,B, and C are curve fitting parameters

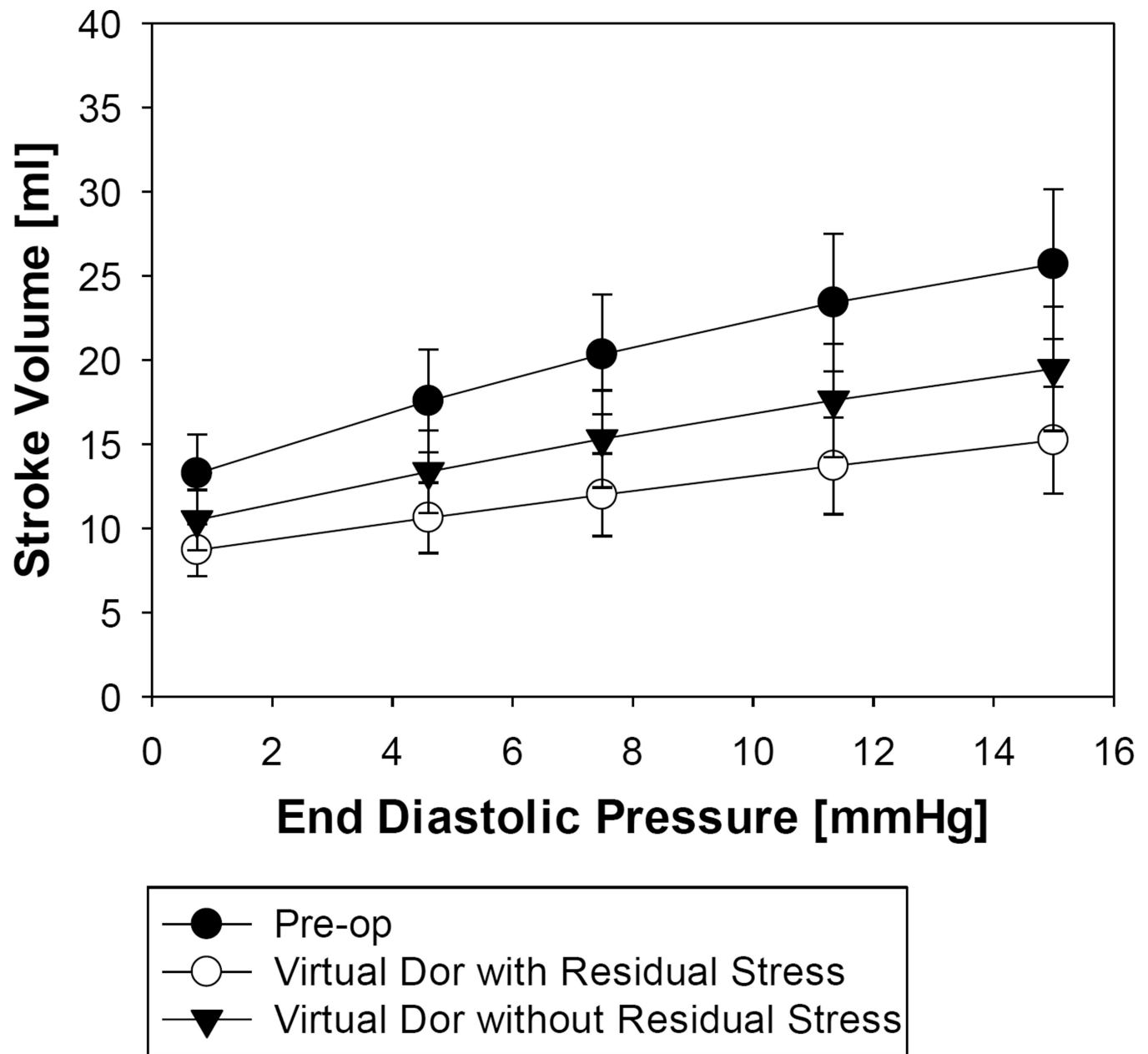


Figure 5.

Average Starling curve relationship curve-fit to $SV = S_1P^2 + S_2P + S_3$ where S_1 , S_2 , and S_3 are quadratic fit parameter.

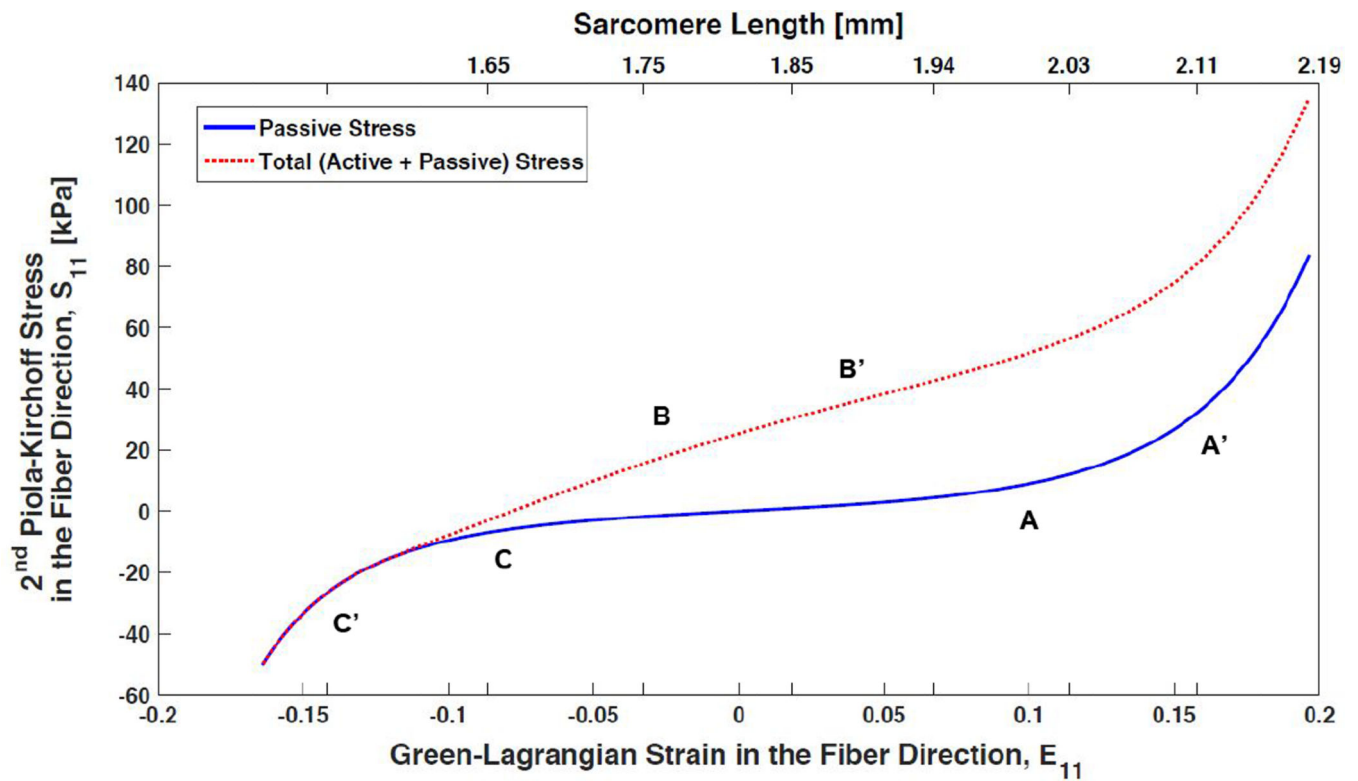


Figure 6.

Behavior of the Guccione passive [22] and active [25] material property laws under tension and compression. Stress and strain were obtained analytically. Passive or diastolic stress strain relationship is in blue and the active or end-systolic stress strain relationship is in red. Strains > 0 represent tension on the myocardium and strains < 0 represent compression. In each case, the effect of additional residual stress is shown i.e. $A \rightarrow A'$ for passive tension.

Table 1

Regional residual stresses at end-diastole and end-systole. All units of myofiber stress are [kPa].

	Residual Stress in the Remote Zone	Residual Stress in the Far BZ	Residual Stress in the Near BZ
End-diastole	0.23±0.40	-5.43±4.88	-180.02±58.48
End-systole	2.89±1.31	-10.39±8.03	-234.15±65.53

Table 2

Effect of Dor on left ventricular myofiber stress at end-diastole. All units of myofiber stress are [kPa].

	Fiber Stress in the Remote Zone at end-diastole	Fiber Stress in the Far BZ at end-diastole	Fiber Stress in the Near BZ at end-diastole
Finite Element Models: PRE-OP	2.78±1.20	3.81±2.10	4.18±2.62
VIRTUAL-DOR+RS	2.11±0.36 [*]	-3.78±4.90 [*]	-177.79±57.26 [*]
VIRTUAL-DOR-NO-RS	2.28±1.08 [*]	1.75±0.88	1.51±0.85 [†]

^{*} = p<0.05 with respect to **PRE-OP**,

[†] = p<0.05 with respect to **VIRTUAL-DOR+RS**.

Table 3

Effect of Dor on left ventricular myofiber stress at end-systole. All units of myofiber stress are [kPa].

	Remote Zone Stress at End- Systole	Far Borderzone Stress at End-Systole	Near Borderzone Stress at End- Systole
Finite Element Models: PRE-OP	34.14±8.10	30.60±9.01	36.36±15.65
VIRTUAL-DOR+RS	31.18±7.47 [*]	6.43±9.46 [*]	-222.17±72.46 [*]
VIRTUAL-DOR-NO-RS	31.93±10.40 [*]	20.71±3.94 ^{*†}	18.82±3.39 [†]

^{*} = p<0.05 with respect to **PRE-OP**,

[†] = p<0.05 with respect to **VIRTUAL-DOR+RS**.

Comparison between experimental data and finite element model results. Volume units are [ml] and pressure units are [mm Hg].

Table 4

	LV Volume at End-diastole	LV Volume at End-systole	Stroke Volume	LV Pressure at End-diastole	LV Pressure at End-systole
MRI Scan: PRE-OP	123.30±14.71	105.77±10.81	17.536±5.21	10.21±2.82	87.31±16.49
Finite Element Models: PRE-OP	123.29±14.66	109.712±11.19	13.58±6.15	10.21±2.82	87.31±16.49
VIRTUAL- DOR+RS	72.03±21.00 [*]	59.69±18.89 [*]	12.34±5.26	10.21±2.82	87.31±16.49
VIRTUAL- DOR-NO-RS	80.66±25.54 ^{*‡}	64.83±21.01 ^{*‡}	15.83±6.32	10.21±2.82	87.31±16.49

^{*} = p<0.05 with respect to **PRE-OP**,

[‡] = p<0.05 and

[#] =p<0.1 with respect to **VIRTUAL- DOR+RS**